A SPATIAL ANALYSIS OF EMERGY OF AN INTERNATIONALLY SHARED DRAINAGE BASIN AND THE IMPLICATIONS FOR POLICY DECISIONS

BY

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A DISSERTATION PRESENTED TO THE GRADUATE SCHOOL OF THE UNIVERSITY OF FLORIDA IN PARTIAL FULFILLMENT OF THE REQUIRMENTS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

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In order to make policy decisions for an internationally shared basin, there needs to be an understanding of the larger systems that may influence the basin and the spatial relationship between resources and development. Ecological and economic components of a basin can be compared using emergy, which sums on the same basis all the energy inputs required. An emergy evaluation and spatial analysis of the Catatumbo River drainage basin, located between Colombia and Venezuela, were conducted to consider alternate management policies.

The Catatumbo basin was divided into watersheds using GIS (geographic information system). The watersheds were categorized by the order of their main

stream. The basin had a maximum stream-order of five. Empower density (sej/m^2/yr) was used to evaluate renewable resources and development. Storages were evaluated using emergy density (sej/m^2). Emergy per volume of river water (sej/m^3) was analyzed to address water-quality problems.

The Colombian emdollar (8E12 sej/\$) is higher than that for Venezuela (6E12 sej/\$). Colombia loses emergy when exchanging goods and services with Venezuela or other countries with a lower ratio. The states containing the basin also have a trade deficit. This practice reduces environmental resources of each system and could affect those of the Catatumbo basin.

Total renewable empower density increases with stream-order watershed (1E12-9E13 sej/m^2/yr). Development increases upstream (1E12-1E16 sej/m^2/yr), but is at a maximum in second-order watersheds (5E17 sej/m^2/yr).

Storages of emergy increase inversely to stream-order watershed (1E12-2E14 sej/m^2). This pattern is due to potential mining materials. Biomass and soils increase downstream.

Emergy per volume of river water increases with stream-order watershed (7E11-6E15 sej/m^3). River sediments influence this pattern. Total nitrogen and phosphorus are within a narrow range (1E9-5E9 sej/m^3). Oil spills in the third and fourth-order watersheds elevate the total emergy in those areas.
Unique biogeophysical characteristics influence the differences in emergy in the Catatumbo basin. Development should be restrained in the Venezuelan watersheds as the renewable energies and large storage of wetlands help buffer

pollutants. Growth in Colombia should be guided so fewer raw materials are traded and better agricultural practices enforced to improve water quality.

INTRODUCTION

Differences in development strategies from country to country can strongly influence the ecological character and self-organizational processes in an internationally shared drainage basin. Often, it can be difficult to ascertain which country receives the majority of the impacts resulting from the contrasting policies. For this reason, problems arising from the various individual management plans for each country may create tensions that require careful planning and cooperation to mediate. A multi-scale management scheme that also compares resources and development using numerical analysis can help the countries involved manage the drainage basin for the benefit of all the countries sharing its borders.

Study of the Catatumbo watershed, shared between Colombia and Venezuela, exemplifies issues that affect international watersheds. Each country has a different management directive for the watershed's resources. For example, development is more accelerated and concentrated in Colombia than on the Venezuelan side. Human activity on either side of the watershed, however, is suspected to contribute various domestic, agricultural, and industrial pollutants flowing into the main river channel.

Two-thirds of the Catatumbo River drainage basin is located in Colombia, where the river originates. The river originates in Colombia and flows northeast

toward Lake Maracaibo in Venezuela as shown in Figure 1. The Catatumbo River is the single most important source of freshwater for the lake contributing 1.57 E10 m^3 of water annually or about 60% of the total freshwater input (Guerrero, 1991; Hernández, 1987; Parra, 1979). In addition to the potential of domestic and industrial discharges reaching Lake Maracaibo, frequent oil spills and high erosion rates threaten water quality of the watershed itself.

Although determining the source of pollutants and assessing local landscape disturbances are important analyses of watershed-management, the challenge of managing the Catatumbo watershed is understanding the impacts of development on the entire watershed. Any watershed impact analysis should include an evaluation of spatial patterns of resources and development (Gosselink et al., 1997; Francis, 1993; Bailey, 1983). A correlation between the two could provide information necessary to understand resource availability and landscape organization.

This study's objective was to understand how the Catatumbo watershed is organized spatially and, through this understanding, propose management alternatives. A spatial study of emergy patterns provided a basis for a comparison of resources and development in the watershed. Emergy is an index of the energy (converted into one type such as solar energy) used or required to make something or run a process (Odum, 1996).

Many terms used in this paper, including those relating to emergy analysis, are defined in Appendix A. In this study, emergy represented the availability of resources and the magnitude of development. The densities of

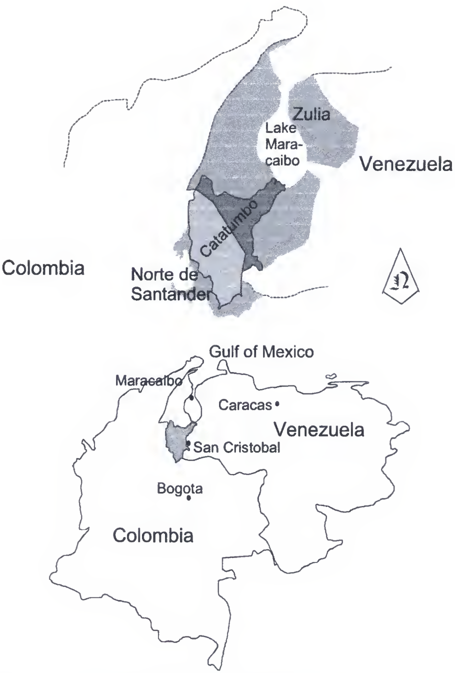


Figure 1. The Catatumbo River drainage basin is located in South America. It is shared between the Venezuelan state of Zulia and the Colombian state of Norte de Santander.

resource storage and development were represented as emergy per unit area. Emergy flows, more commonly known as measures of empower or emergy per unit time, represented resource flows and economic development.

It was predicted that the spatial organization of the watershed could be described by analyzing the distribution of the watershed's resources in terms of empower using a perspective based on the watershed's basins and sub-basins. Resources contributing to the organization of the watershed could include those derived from environmental inputs (such as rain, river geo-potential, sediment load, and storages of minerals and vegetation) and from human systems such as agricultural and urban centers. An examination of the watershed's spatial organization, including the relationship between resources and development, could be used as a basis to determine management alternatives.

The predicted spatial organization of the watershed was of a longitudinal pattern in a downstream direction. Empower was believed to increase in a hierarchical manner from upstream, where resources were lower, and disperse to downstream, were certain resources accumulate. This prediction was derived from current theories in watershed and stream ecology. These theories include the hierarchical order of geo-potential energies in watersheds (Romitelli, 1997; Diamond, 1984) and longitudinal organizational patterns of streams as described by the river-continuum concept or RCC (Vannote et al. 1980).

At the scale of the river and its tributaries, this study predicted that relationships could be derived between the spatial organization of the watershed and development to known water quality and quantity of the Catatumbo River

and its tributaries. Water quality may be described using the emergy in a volume of river water measured at specific water-monitoring stations. The emergy in a volume of river water of the constituents, as well as the emergy of the water itself, could be compared to development empower located in the same watershed to a monitoring station.

This study evaluated the spatial patterns of flows, storages, and water quality in the Catatumbo drainage basin as the watersheds, or sub-basins, delineate them. Using this basin perspective as a foundation, several questions arose of how the watershed might be spatially organized and how that organization might affect the relationship between resources and development. These questions included the following:

- Is there a longitudinal spatial trend of flows, storages, and water quality?
- Can a trend of flows, storages, and water quality be discerned by stream-order?
- Does development locate where empower flows are high?
- Are emergy flows (empower) of renewable resources or development related to emergy storages of resources located in the same watershed?
- Is there a relationship between the spatial pattern of development and emergy of water or emergy of water quality (constituents)?
- Is there a distinctive longitudinal pattern of transport ratios that compare the geo-potential emergy available to the emergy of river water constituents?
- What management alternatives can be derived using the understanding of the spatial pattern of watersheds and river-water quality in terms of emergy?

Literature Review

A review was conducted on the need for watershed-management and the particular concerns for internationally shared watershed systems. Few published examples of watershed-management in the tropics and developing countries were found. Next follows a summary of current thoughts on the structure and ecological organization of rivers and watersheds. Common impacts to watersheds due to development were reviewed, but only one example of how development might affect predications of stream organization based on the river-continuum concept. Finally, studies conducted on watershed organization in terms of emergy were summarized.

Watershed-management Policies

Worldwide, watersheds and their river channels are being subjected to rapidly changing economies and growing populations. Individual watershed-management plans, concerning only a single country, are ineffective to handle unpredictable impacts initiated in other parts of the watershed. French (1994) points out that many international agreements already exist that are designed to protect the environment, but the success of the agreements largely depends on the extent to which they are politically oriented as opposed to environmentally oriented. Policies meant to please the most reluctant country to participate are often destined to fail.

Due to the self-interests of most countries, a country without a water-resource policy of its own is unlikely to participate at the next higher scale of supporting an international policy. Lacking water policy at any level puts the

protection of their resources, including water quality and supply, at risk because the availability of those resources may be dependent on the actions of other countries. Management plans concerning watersheds shared between developing countries are especially uncommon making those watersheds particularly susceptible to water contamination (Krysanova and Kaganovich, 1994; Allan and Flecker, 1993). If international agreements do exist, any reference to watershed-management is often vague or excludes enforceable policies to control contamination as in the case for agreements between Venezuela and Colombia (Muci, 1994).

It is unlikely that developing countries would propose stringent policies for water-resource management even for their own resources (Casadei, 1987; Dourojeanni and Nelson, 1987). Finding the sources of watershed contamination and evaluating the potential impact is difficult because often the technology or resources are lacking to do so. Political issues also arise that can inhibit research; thereby affecting the validation of the pollution sources, assessment of negative impacts downstream, and determination of responsibility.

According to Scudder (1994), the idea of integrated or basin-wide watershed-management planning has not received sufficient attention in the tropics and subtropics. At fault is the inability to envision the opportunities for regional economic growth and environmental protection. Developing countries often have difficulty initiating watershed-management plans. The national economies are in major flux creating areas of intense growth where natural resources are in abundance so that immediate investments in infrastructure are

thought not to be required (Miloradov, 1992; Hooker, 1994). The inevitable results, according to Kirkpatrick (1992), are that water demand quickly surpasses the threshold of available supply, and other resources are quickly depleted such as forest wood and top soil. In addition, the potential for water-mediated pollution increases if there are no management controls to address erosion, runoff, or water treatment.

Countries that share a watershed usually balance their interests with economic losses and gains and react accordingly without regard to the potential downstream impacts of their activities. It is common for countries to overlook the loss of ecological function due to water problems, including the alteration of whole habitats (Francis, 1993). In other words, if polluting is profitable for the countries located upstream, then they will continue to do so even if communities downstream suffer the affects of poor water quality. Economic resources derived from the watershed impact both upstream and downstream communities. At some point, ecological degradation may be unrecoverable. It may be only after this occurs that governments decide to take action and formulate policy to protect their watershed.

The impetus for requiring a watershed-management plan generally comes after some level of development or development impact has already occurred especially in second- and third-world countries. The type of management plan that evolves depends largely on the priority and immediate needs of the governing agencies. As a result of many years of trial and error with politically oriented policies, watershed-management is becoming oriented toward the idea

of controlling pollutants and water use by managing development on a watershed scale (McCaffery, 1991; Christianson and Arcury, 1992; Wolfe, 1992).

Development plans are now more commonly, but not universally, based on the geographic topography and ecological organization of the entire watershed basin regardless of international political boundaries. Many watershed plans use the landscape-analysis capabilities of geographic information systems (GIS) to enhance the variety and accuracy of large-scale data required for basin-wide management. Even some developing countries are turning to GIS to improve their efforts towards watershed-management (Sheng et al., 1997).

The term "sustainable development" is often invoked to describe the main goal of watershed-management. For a development to be sustainable it must be able to use the watershed's resources in a manner that does not compromise the future availability of those resources (Gardner, 1989). It is believed sustainable development is possible only if it is understood how the consequences of development affect and are affected by human activity occurring in both upstream and downstream areas of a watershed system (Wolfe, 1992; Francis, 1993; Sadler, 1993).

Based on a survey of inhabitants of the Kentucky Stream watershed, Christianson and Arcury (1992) proposed that local interests and opinions concerning management alternatives are often similar throughout a watershed. Therefore, managing the watershed requires communication on the watershed scale. On the other hand, a watershed-management plan can become overly

complex and impede the potential for sustainable development if all the governing agencies resist compromise. This was the case for the Bicol River Basin Development Program in the Philippines (Koppel, 1987). Success of the Nigeria Stream watershed-management plan depended on the cooperation of nine countries (Kalapula, 1989). Each country had to propose, coordinate, and modify their expectations for development potential of the watershed's fisheries, agriculture, wildlife, forestry, and tourism.

Management plans for watersheds tend to fail when the effects of development on the local resources are not considered. For example, China's government, decided to invest millions of dollars for the development of the Yangtze River to boost that area's independence from import goods and services and to add to the country's main economic base (Tong, 1994). Development's attraction to the watershed is for the extensive fisheries and floodplains. The management plans for the watershed, however, center on the exploitation of the natural resources with little attention to resource conservation, water quality, or sustainable development.

Using management plans that consider the entire drainage area of the watershed can allow additional benefits other than the inclusion of all governing agencies in the planning process. Gosselink et al. (1997) encouraged the use of basin-wide studies for the evaluation of cumulative impact assessments and management. They applied a watershed-wide project scope to study the Tensas Stream watershed in the lower Mississippi valley. Research and implementation of a multi-state watershed-management plan for the Platt River resulted in side

benefits such as restored wetlands for wildlife use and improvements in overall water quality (Lathrop, 1995).

Ecosystem management for watershed planning is becoming an effectual means of organizing land use and resource management. It focuses on the protection and maintenance of ecosystem functions, and generally requires the study and planning of the entire watershed basin (Francis, 1993). An application of ecosystem management planning for a watershed was done for the Tennessee Stream watershed located in North Carolina and Georgia (Wear et al., 1996). Their study showed that the management of only public lands to protect the ecological functions of watersheds is futile if done without respect to the overall spatial arrangement of all major land uses and ecosystems in the basin, including private ownership and development areas.

Spatial Organization of River Systems

The scale of this study falls between the spatial scales of stream system and segment system according to the spatial organization classification scheme designed by Frissel et al. (1986). Their system of stream organization suggests there is a hierarchical system over space and time for streams beginning with the microhabitat up to the stream system or scale of the main river channel. Beyond the scale of the river system is the watershed, which includes all surface water that flows into the river channel or is formed as a result of river flooding. The watershed also includes terrestrial areas that contribute runoff (over land flow) into the main river channel.

It is widely accepted that the development and physical characteristics of a river system are dependent upon the geologic history and climate of its drainage basin (Hack, 1957; Schumm and Lichty, 1965, Douglas, 1977). The geologic forces that are responsible for the development of most river or stream systems include such phenomena as tectonic uplift, subsidence, folding, faulting, volcanism, glaciation, and climatic or sea-level changes. The same forces in combination with weathering and erosion (and any human alternations to the landscape) determine the geo-potential of stream-segments.

The development of the river and its watershed basin involves headward and lateral extension of the channel network and lowering of basin relief by surface erosion (Horton, 1945) or groundwater-mediated processes (Higgins, 1984). The time scale for these processes can extend into several centuries. Research by Richards (1982) and Stolum (1996) also suggest that river meandering has a strong influence on the self-organization of river morphology. River meandering is the continual occurrence of natural alterations in the river-channel platform due to the constant erosion and deposition of sediments induced by water flow.

Comparing river systems is possible if classified according to the biogeoclimatic region in which they are located (Warren, 1979; Bailey, 1983). Other useful classifications would be the slope and shape of their longitudinal profiles and some index of the drainage network structure. According to Frissel et al. (1986), thinking at the spatial scale of the river system is necessary for planning watershed-management activities, especially over the long term.

One scale down from the stream or river system is the segment system. Ideally, a segment represents a portion of the stream that flows through a single bedrock type and is bounded by tributary junctions or major waterfalls. In addition, a segment has relatively uniform slope along its length. The potential capacity or geo-potential of a stream-segment is dependent on the same forces acting on the larger scale watershed. Additional forces at the stream-segment scale include the slow upstream migration of nick-points and down-wearing, widening, or extensive
in-filling of the valley floor, (West, 1975), development of new channel heads (Douglas, 1977), and other processes measurable on a time scale of many centuries.

Drainage areas, and thus hydrologic characteristics, abruptly change at tributary junctions. At these intersections, changes can occur in bed-material size, shape, and lithology (Hack, 1957; Miller, 1958; Knighton, 1982). Water chemistry patterns can also be altered where tributaries converge (Teti, 1984). As will be briefly discussed later in this section, Vannote et al. (1980) and others described discrete changes in stream macroinvertebrate communities below tributary junctures, thus between segments.

To understand the physical organization of stream-segments, Strahler (1957) introduced the notion of "stream-order". Stream-order indexes increase as small streams merge together to form larger tributaries, then those tributaries merge together to form even larger tributaries. This process continues until only the final river channel remains. Assigning stream-orders is theoretically easy as

shown in Figure 2. Each successive convergence of two tributaries of the same size, and therefore stream-order, increases the stream-order of the resulting stream by one more than that of the tributaries that formed it. The final stream-order, however, depends on the scale of the maps used to determine stream-order; therefore, one must be cautious when comparing more than one river strictly by stream-orders.

One can infer the size of the river and some of its basic organizational characteristics if the final stream-order of its main channel is known. As the stream-order increases, definite changes in the attributes of the tributaries take place. Theoretically, stream-orders of the same magnitude are comparable in such characteristics as discharge, length, and channel width (Leopold et al., 1964; Leopold and Madock, 1953). Moreover, the functions or dominant processes occurring at each stream-order are somewhat predictable. Diamond (1984) justifies the utility of the Strahler method by demonstrating the increase in geo-potential energy flux and transformity with stream-order in the Mississippi River. Thus, stream-orders represent longitudinal steps in the energy-transformation chain of rivers as illustrated graphically in Figure 2b (Odum 1996).

Currently, one of the most widely known and accepted perspectives on the ecological aspects of stream development uses stream-orders as an organizing feature of riverine structure. Vannote et al. (1980) first introduced the hypothesis known as the "river-continuum concept". The river-continuum concept has evolved over the past 20 years. As it now is understood, the concept stresses a holistic approach to stream ecology that includes the following: 1) the physical

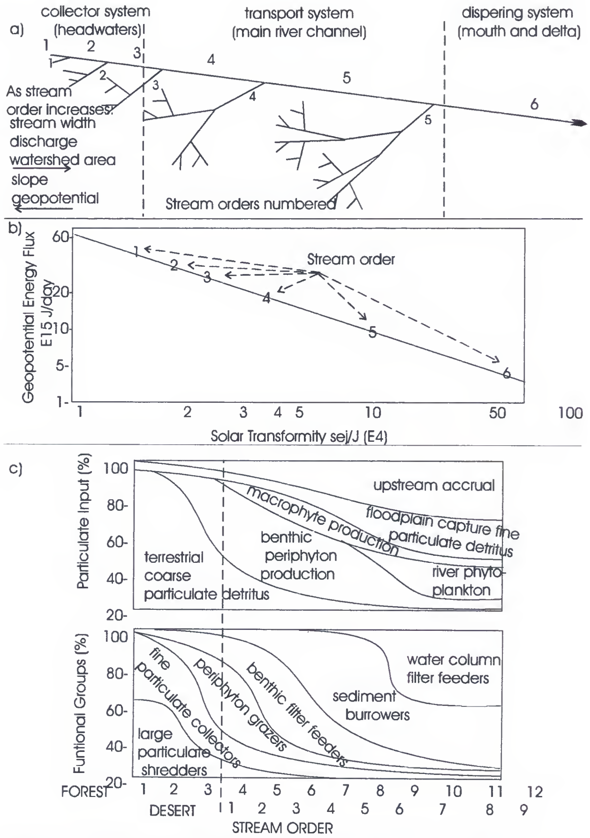


Figure 2. This figure summaries three related stream development theories: a) example of stream order hierachary (Strahler 1957); b) transformity of Mississippi River stream orders based on river geopotential energies (Diamond 1984); and c) predicted organization of biological characteristics by stream order following the

and biological organization of river systems; 2) the flexibility or "sliding-scale" adaptability of ecological characteristics to changing conditions of a stream's physical environment; and 3) material cycling in open systems (Minshall et al., 1985). Some of the characteristics that are predicted to change with stream-order are shown in Figure 2c.

The Impact of Development

From the point of view of development, the surface water that possess the most favorable characteristics for human settlement or use are rivers. For this reason, large civilizations are usually located in a watershed, where there is at least a convenient water supply, fisheries, navigable water to aid commerce, and in many cases hydroelectric potential.

Although development along many river systems seems to follow the river's course and concentrate at major junctions and possibly above the delta area, development in some watersheds must cluster wherever the landscape or climate will allow. For example, the Colorado River system has only clustered settlements and no continuous transportation system that parallels the river along its course. The principle barriers to development are the rugged terrain and entrenched river channels. The fragmented centers of development along the Colorado River have made the management of the entire basin more difficult as well as the complications of it crossing six states and part of two countries (Stevens, 1994). A consequence of the discontinuous watershed landscape is that resource exploitation concentrates where convenient to development, making the local availability of resources uncertain in the long term.

Climate can also limit the success of development in a watershed. The occupation of areas with intense rainfall or extreme differences in the rainy and dry seasons can require much effort on the part of the potential inhabitants to cope with the high fluctuations of the seasonal floods. The Amazon River system and other tropical rivers are examples of such areas. Difficult climatic conditions combined with the remoteness of some watersheds to established urban centers can slow the arrival or progress of human activity in those areas (Brozovic et al., 1997).

History has shown that if the resource are valuable enough and desired enough, a way is generally found sooner or later to get to them, even in remote watersheds. Grey (1994) summarizes how development progressed, albeit at times slowly, across the American West during its early settlement. The building of roads, bridges, and train tracks allowed access to potentially rich natural resources and provided transportation between new settlements. Most of the permanent settlements were along rivers. Even in prehistoric times, humans tended to congregate near river systems (Petersen and Matthews, 1987). With the exception of industrial pollution, the impact of development on watersheds was much the same then as it is now.

Human activity has altered most of the world's seventy-nine large river systems, including the floodplains (Welcomme, 1985). Many smaller watersheds have at least some development in one form or another, and the remainder already has or will face the same challenges imposed by human occupation.

Watersheds in developing countries are at particular risk due to the potential impacts of development. These areas commonly serve the needs of the entire country or a large portion of it (Sparks, 1995). If a large region depends on the resources of only one watershed, then the ecosystems of that river system are likely under great stress. If that watershed is shared between two or more countries that depend heavily on its resources, then uncontrolled development pressures might lead to rapid depletion of natural-resource storages and to potentially contaminated water.

Venezuela and Colombia's river systems are no exception to the extreme negative impacts of development (Valle and Taphorn, 1984). Impacts such as species extinction, biological mutations due to contamination (especially heavy metals), permanent losses of topsoil, and complete alteration of entire riverine ecosystems have affected various river systems, including the Orinocco River. The loss of certain ecosystems, such as forested wetlands, can reduce or eliminate ecological functions that are of benefit to human development (Gosselink et al., 1997). These functions can include moderation of downstream flooding, maintenance of good water quality, and provision of diverse habitats for wildlife (Wharton et al., 1982).

Research conducted by Wiley et al. (1989) showed that development such as agriculture can dramatically change the predicted river-continuum pattern by redistributing available nutrients, removing vegetative structure, and diverting water flow. In effect, the predicted stages of longitudinal organization along the river can be less clearly delineated or even reversed compared to what would be

expected in an undisturbed watershed (see Figure 2). Moreover, parts of the river with floodplains can be more or less productive as would be predicted. If flow regimes are altered, then biological communities upstream can also dominate downstream areas by taking advantage of the changing environmental conditions such as reduced flooding.

Sparks (1995) emphasized that the floodplains of a river are especially attractive for development because of the potential for profitable fisheries and fertile soil. Agricultural areas in the floodplains of a watershed, however, are vulnerable to upstream development activities that can seriously affect crop success (Kimmage and Adams, 1992). Common threats to agriculture include increased erosion, reduced water quality, and upstream diversion of or retention of water flow, which prevents use of water.

Development is most likely to have significant impacts on rivers with diverse habitats along the course and in the floodplain (Schmier and Zclewski, 1992). These kinds of rivers are likely to be highly productive, and any alterations of the natural flow regime or significant changes in water quality can potentially reduce habitat diversity. In the tropics, where bio-diversity and species richness is highest in the floodplain, upstream activities can potentially completely change the balance of a river's biological communities.

The potential impact of stream-water contamination is as varied as the types of pollutants present in the watershed. A common source of contamination is resource mismanagement. Mismanagement can include, for example, unregulated cutting of forests, poor management of topsoil by agricultural

activities, over fishing, or the use of a stream basin as a catchment for domestic or industrial discharge. This is a serious problem because runoff can transport all the pollutants, regardless of their source, to the river channel. The combination of many pollutants can alter the impact of each pollutant individually by increasing, decreasing, or changing their side effects, creating an even more complex watershed-management issue (Laws 1993, Haslam 1990).

Abrupt changes in water quality can bring about large-scale population disturbances in aquatic systems (Kaufman, 1992; Sarokin and Schulkin, 1992). Common catalyses for sudden drops in water quality can include inputs of chlorinated organic pollutants (e.g., PCB, DDT) or suspended sediment from increased erosion. In a river, increased sediment loads initiated from heavy rains and erosion can cause sudden fish kills such as occurred in 1992 in the Catatumbo Stream watershed (Rodriguez, 1992). The high erosion rate was blamed on poor soil-management practices used by agricultural and forestry operations in the watershed. Significant changes in the community structure of the fish populations of certain watersheds in Africa is blamed on a variety of impacts generated by poor land-use practices forestry, exotic-species introductions, and development (Kaufman, 1992).

A well-managed watershed will reduce the impacts of contamination. Preventing or restoring impaired river systems can also have significant economic advantages such as long term sustainable fisheries (Bayley, 1995). Appropriately managing the river also benefits larger scale activities, such as

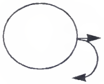
forestry and agriculture, providing the floodplain area is intact and non-point pollution sources are minimized.

Emergy Analysis

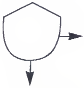
Usually questions of development, management policy, and resource use involve weighing environmental impacts against economic gains. Most often impacts and benefits are quantified in different units resulting in a paralysis of the decision-making process because no common means of evaluating the trade-off between environment and development occurs.

Emergy theory (spelled with an "m") focuses on the measurement of the amount of energy to produce something in nature or to more accurately account for environmental contributions to the economy (Odum 1996, 1994a, 1994b). Emergy analysis includes evaluations of both environmental and economic components of a system. The specific methodology can include comparisons of the driving forces of the system(s) under study, definition of important system components using diagrams and numerical analysis, and/or simulation modeling of the system's productivity. Common energy symbols used in systems diagrams and modelings are given in Figure 3.

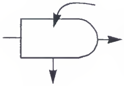
Over the last twenty-five years, emergy theory and systems analysis have been refined and applied as a basis for policy decision making. Emergy theory has its roots in the study of energy and general thermodynamic principles that began in the 18th century. A main premise is that because both environmental and economic parts of a human-populated system require energy, it is necessary to measure the contributions of both on a common basis. Money is insufficient to



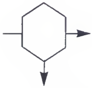
OUTSIDE ENERGY SOURCE- delivers energy flow from outside the system; a forcing function.



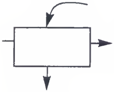
ENERGY STORAGE TANK-stores and delivers energy flows; a state variable.



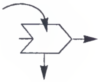
PRODUCER-converts and concentrates solar energy, self-maintaining; details may be shown inside.



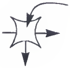
CONSUMER-uses high quality energy and feeds it back autocatalytically to improve flow, self-maintaining; details may be shown inside.



GENERAL PURPOSE BOX-for any sub-unit needed, is labeled to indicate use.



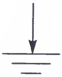
ENERGY INTERACTION-interactive intersection of two or more pathways coupled to produce an outflow in proportion to a function of both; work gate.



SWITCHING ACTION-flow controlled by on or off switching actions.

P

ENERGY-M0NEY TRANSACTION-money flows (dotted line) in exchange for energy (solid line). Price (P) is shown as an external source.



HEAT SINK-drains out degraded energy after its use in work.

Figure 3. Energy language symbols (Odum 1994).

make such comparisons because it only measures human services. It also does not represent all the direct contributions of nature to human systems, such as the recycle of nutrients. Money can only represent the values of transactions occurring in the economic sectors of human systems.

Each emergy analysis is an evaluation of a system of predetermined boundaries. Common terms used in emergy analysis are defined in the glossary provided on page 201. This type of analysis includes an examination of the organizing, driving forces outside the system's boundary and their influence as they interact crossing the boundary. These forces include environmental energies (i.e., sunlight, rain, geo-thermal heat) and economic energies derived from purchased imports from other systems. Primary production processes in nature directly transform some of the driving forces into chemical energy. This energy is transformed for internal use and for interactions with components of other systems outside the boundary (e.g., obtaining more energy resources).

Emergy analysis includes the economic factors that influence both human and environmental systems if only indirectly. The economic system, in emergy analyses, is a sector of the larger energy system. This analysis puts everything within it on common terms. This allows the comparison of a forestry operation and a fishing business on the same basis.

The calculation of emergy involves converting all sources, processes and products into energy, mass, or monetary terms. These units are converted to a common basis by multiplying by the emergy per unit of a specific measure (emergy per weight, emergy per money, or emergy per unit energy). Emergy per

unit energy is called transformity. Solar transformity is the relationship between equivalent solar energy required to make a product or service and its actual energy content. All independent, contributing resources to a productive process, evaluated in solar emergy, are summed together as a numerator divided by the observed or actual energy content. The units of transformity, therefore, are solar emjoules per joule (sej/J). Transformity also represents energy quality (Odum 1996).

In a systems diagram, items are conventionally arranged in systems diagrams from left to right to reflect a component's influence on different processes existing at the scale of the diagram. Items on the left side of the diagrams have higher quantities of energy than those on the right (e.g. Figure 4). However, items on the left side of the diagrams have lower transformities than items on the right side. Hence, items on the left side of the diagrams have smaller regions of influence and require less to be maintained on the same relative scale as items on the right. Items on the extreme right can affect the items to their left in the diagram much quicker than the other way around.

Water at the Scale of the Watershed and River

Energy systems procedures represent realms of different scale (Odum 1996). A drainage basin analysis includes a comparison of its watersheds as a system to determine the basin's contributions to and resources received from the other, larger scale, human economies and environments. Studying a system at different scales can help guide future policy by taking into account how the actions at one scale affect responses at other scales.

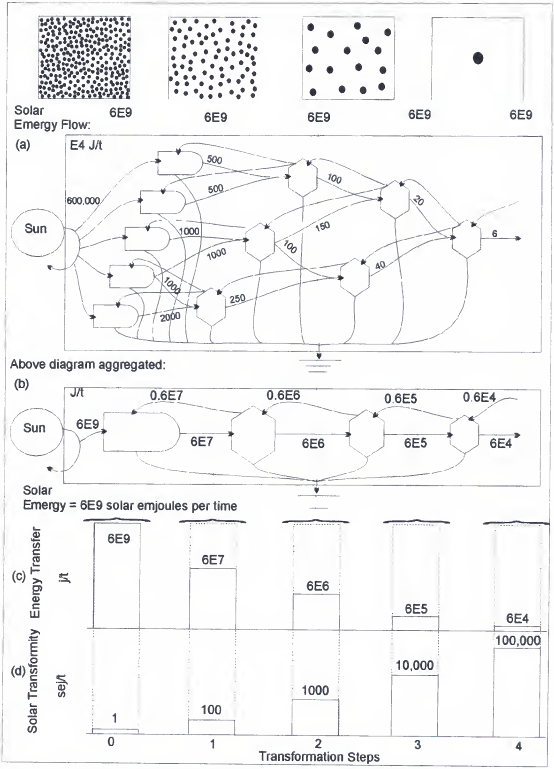


Figure 4.. Energy transformations and hierarchical ordering of ecosystems illustrating the concept of solar emergy: (a) spatial pattern; (b) system network; (c) network aggregation by hierarchical levels; (d) energy flows; and (e) solar transformaties (from Odum 1993).

In addition to studying the larger scale characteristics of a system, understanding the system at a smaller scale is equally useful. The scale at which the characteristics of a system are being studied influences the relevancy of the various properties of each component. For example, the most relevant properties of water at the scale of the watershed are somewhat different from those at the smaller scale of the river itself.

At the watershed scale, important properties include the availability of the water, its ability to erode the rock surface and release nutrient rich sediments, and the water's capacity to transport those sediments and other water mediated materials downstream. Other characteristics important to human developments include the potential for the water's movement to provide free services for developments such as hydroelectric power and transportation.

In contrast, water quality, or more precisely the quantity and availability of constituents within the water, is the important property of water at the scale of the river. Water quality affects the productivity of river-side ecosystems and downstream systems, but it may not affect the watershed as a whole nor its human developments, unless potable water is required.

The important properties of water in terms of emergy content are different depending on the scale at which the water was measured or studied. More emergy is contributed to the water when earth processes or human economy concentrates it into large volumes in lakes, groundwater, lower reaches of rivers, or giant tanks. Much less emergy is required if the water was widely distributed such as rain over land or in the ocean. The result in a watershed is that the

volume of water is concentrated as streams converge to form higher stream orders. Hence, the emergy flow of water in a watershed should increase with stream order.

The average emergy of water, exclusive of its constituents, as a volume at the scale of the river, however, would not necessarily increase with stream order if the morphology of the river was such that some of the lower-order streams in one part of the drainage basin were actually larger than some higher-order streams in another area. A real river is not a simple network of equally increasing streams in all parts of its drainage basin. Therefore, at the river scale, the emergy of the water per volume, while generally increasing with stream order may not increase consistently when calculated as an average.

The significance of this is that development plans must consider the possibly greater influence human activity may have on the geo-potential emergy per volume of some lower-order watersheds than others downstream and how the impacts may in turn affect the downstream system. Romitelli (1997) discusses in detail how important geo-potential emergy is to the ecological processes of floodplain and esturary ecosystems.

Empower and Development in Watersheds

Empower density is the emergy flow per unit area per time. Often empower density is measured as the flow of solar emjoules per square meter per year. It is high in cities, waterfalls, and beaches (Odum, 1993). Generally, higher empower density implies more use of the available resources (Odum, 1996). Policies using the empower density pattern, as it is organized in a

particular watershed, may guide future development of environmental and economic resources. Areas of high empower density may indicate a prosperous center of active development growth or a red flag showing the location of wasteful resource use. Human development may increase empower density in a watershed over the long term as long as the activities are not so intense or destructive as to reduce the renewable, flow-limited resources below useful recovery levels.

According to Odum (1986, 1997) and Romitelli (1997), resources may organize by means of spatial succession. In the case of a watershed with converging streams, resources transform in a downstream direction into more concentrated forms of available energy. Diamond (1984) demonstrated that the transformity of river geo-potenial energy increases with stream-order in the Mississippi River. Another example of longitudinal organization in a watershed comes from Odum et al. (1986). The directions of empower flows from the environment, and development flows may be inversely correlated in many watersheds because of the location of resource storages upstream such as groundwater and minerals.

Other measures than empower may be more appropriate for evaluating the organizational pattern of the stream water. One example is emergy per unit volume or unit mass, which can represent emergy in a volume of river water. This measure may be especially useful for the study of water quality. Greater emergy means more available energy went into the production and maintenance

of a product. Items that require more energy may be replaced or discontinued unless they have large effects commensurate with those impacts.

In a river, the controlling organizational factor of water quality may be emergy in a volume of river water such as sej/liter. Development along the river or tributary may influence the level of emergy in a volume of river water by increasing the levels of certain compounds. Emergy in a volume of river water could decrease downstream if high emergy contents are filtered out. Various ecological and physical processes associated with a river ecosystem such as biological uptake, evaporation, or sedimentation, may remove undesirable substances from the river water. However, high loads of sediments or pollutants in a river may reach downstream ecosystems beyond the watershed.

A series of studies in the area of eco-toxicology demonstrated that compounds and elements with higher transformities had greater potential to bioaccumulate and be more toxic (Genoni, 1995a; 1995b; 1996; Genoni and Montague, 1997). The higher the transformity of those compounds, the more impact they could have on downstream systems. Such materials may increase productivity in an area adapted to use them such as a floodplain with fertile soils. The materials may instead be negative in a poorly adapted area, such as where the presence of toxic wastes or high nutrient loads weaken valley fisheries. Therefore, river management may include the priority treatment or reduction of high transformity materials that reduce the water quality and raise emergy in a volume of river water.

One way to test the impact potential for a substance in water could be to compare its emergy in a volume of river water with that of other substances. If the emergy of a substance in a volume of river water is higher in one place than at a different location, then the potential for its impact on the watershed is greater at that place as compared to the other location.

Plan of Study

This research evaluated the larger scale systems and the spatial organization of the Catatumbo River drainage basin using emergy flow, storage, and water quality. The analyses were done to provide an understanding of how to develop management alternatives for an internationally shared basin.

The emergy analyses of the national regions included evaluations of Venezuela and Colombia. Analyses of the states containing the watershed, Zulia in Venezuela and Norte de Santander in Colombia, were included to provide a perspective of the different flows of emergy dominant in each state.

The spatial analyses at the scale of the drainage basin involved evaluations of empower density and emergy storage. The spatial analysis of the watershed involved the evaluation of various maps of the watershed. Each map had an associated database that was used to convert the spatial data as necessary for other analyses. The maps were created in four groups, which included the creation of base maps, the determination of the watersheds (also known as sub-basins), and maps of empower density. The spatial perspectives used in this study were segment watersheds and watersheds grouped by stream-order.

The next section of this stage evaluated the emergy in a volume of river water of various constituents. The constituents included phosphorus, nitrogen, river sediment, and oil. The emergy of water and a transport efficiency of each constituent were also determined.

Management alternatives for the watershed were suggested based on the results of this study. The effect of reoccurring oil spills in certain areas of the watershed was included to provide an example of specific water-quality problems facing managers of this particular watershed.

METHODS

The methods for this study include an overview of the larger systems of which the drainage basin is a part and a spatial analysis of the basin itself. The larger systems included the countries that share the international boundaries of the drainage basin (Venezuela and Colombia) and the systems which share the drainage basin on a state level (Zulia and Norte de Santander). The overview of the countries and states was performed using emergy analysis to help understand how the drainage basin may be affected by larger scale economies. The spatial analysis was performed using GIS to examine the spatial pattern of resources in the drainage basin in terms of emergy.

Emergy Analysis

"Top-down" systems-analysis methodology guided the evaluation of the regions sharing borders in the Catatumbo River drainage basin. Emergy flows were compared on the national and state levels. The emergy-analysis methodology followed the guidelines given in Odum (1996). Systems diagrams were drawn to pictorially represent the important sources, components, and interactions between those components of each system. Each analysis included a final table listing the energy flow, transformity, empower (energy flow times transformity), and em-dollar (total system empower divided by the system's gross

domestic product in US dollars) of each major flow depicted in the diagram. United States dollars were used because the values of Venezuelan and Colombian currency on the international market have changed significantly in the last five years making it more difficult to relate the results to any future studies. The caloric values, transformities, and emergy per mass used in this study are provided in Appendix B. Calculations of the regional energy flows and sources of data used in this study are provided in Appendix C.

Special emergy indices, listed in Table 1 and shown graphically in Figure 5, were calculated to compare the environmental and economic flows of each system. National level emergy analyses included comparisons of the emergy indices for both Venezuela and Colombia. Similar regional analyses included comparisons between the Venezuelan State of Zulia and the Colombian State of Norte de Santander.

Spatial Analysis

Spatial analysis of emergy in the Catatumbo drainage basin was conducted using GIS. Each map of the drainage basin had an associated database that included information about the sources, flows, and storages of resources in each watershed. Moreover, the combination, or electronic overlaying, of certain base maps (described in the next section) provided a means of generating additional maps used to calculate emergy. Subsequently, spatial correlations of the general pattern of emergy in the watersheds was done to assess the relationship between the location of development and environmental resources in the drainage basin.

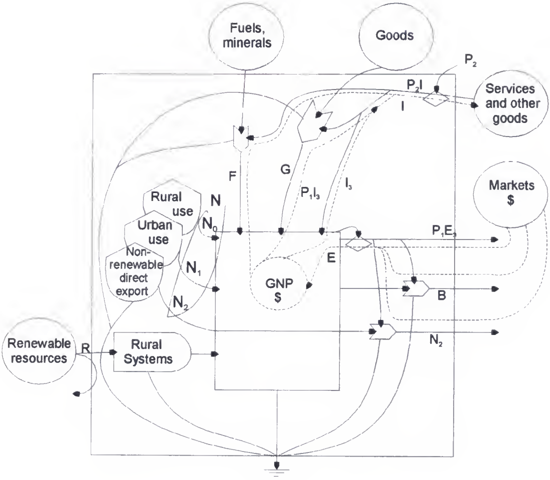
Table 1. Overview indices of annual solar emergy-use, origin, and economic and demographic relations.

Name of Index	Derivation	Quantity	Unit
1 Renewable solar emergy flow (rain, tides, earth heat flows)	R	****	sej/yr
2 Solar emergy flow from indigenous nonrewable reserves	N	****	sej/yr
3 Flow of imported solar emergy	$F+G+P_2I$	****	sej/yr
4 Total emergy flows	$R+N+F+G+P_2I$	****	sej/yr
5 Total emergy used, U	$R+N_0+N_1+F+G+P_2I$	****	sej/yr
6 Economic component	U-R	****	sej/yr
7 Total exported solar emergy	N_2+B+P_1E	****	sej/yr
8 Percent locally renewable (free)	R/U	****	%
9 Economic/environment ratio	(U-R)/R	****	
10 Ratio of imports to exports	$(F+G+P_2I)/(N_2+B+P_1E)$	****	
11 Ratio of exports to imports	$(N_2+B+P_1E)/(F+G+P_2I)$	****	
12 New solar emergy deficit due to trade (imports minus exports)	$(F+G+P_2I)-(N_2+B+P_1E)$	****	sej/yr
13 % solar emergy-use purchased	$(F+G+P_2I)/U$	****	%
14 % solar emergy-use derived from home sources	$(N_0+N_1+R)/U$	****	%
15 Solar emergy-use per unit area	U/area	****	sej/m^2
16 Solar emergy-use per person	U/population	****	sej/per.
17 Renewable carrying capacity at present living standard	(R/U)*population	****	people
18 Developed carrying capacity at same living standard	8*(R/U)*population	****	people
19 Solar emergy-use to GDP	$P_1=U/GDP_{1992}$	****	sej/$
20 % Electric	(electrical use)/U	****	%
21 % Fossil fuels	(fuel use)/U	****	%
22 Fuel-use per person	(fuel use)/population	****	sej/per.

Table 1. --continued.

Definitions of symbols used in this table and in Figure 4 that are not defined above.

B	Export of manufactured goods
E	Total exported goods
F	Imported fuels
G	Imported goods
I	Total imported goods and services
N_0	Non-renewable resources for rural use
N_1	Non-renewable resources for urban use
N_2	Non-renewable resources (for direct export with minimal processing)
P_1 E	Income (price) of exported goods (aka emergy to dollar ratio for country)
P_2I	Price of imports (including external value) (aka emergy to dollar ratio for world)



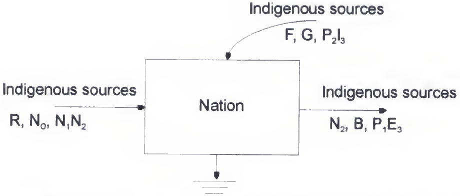


Figure 5. Overview systems diagram of a nation, its environmental resource base, economic component, imports and exports: (a) main flows of money and solar emergy; (b) definitions for summing emergy inflows and outflows (from Odum 1994). Variables also refer to emergy ratio equations shown in Table 1.

Base Maps

The GIS program ArcCAD, version 11.2, was used to digitize maps of the watershed, and Excel version 5.0 (spreadsheet program) was used to make calculations and assess map results. Thematic maps (1:500,000) were digitized from maps electronically scanned out of Aguirre et al. (1989) and Ecopetrol and Intevep (1996). The coordinates of the digitized maps were converted into real world units by converting the original geographic longitude-latitude degrees into a Universal Transverse Mercator (UTM) coordinate system measured in meters.

The digitized maps were converted to ArcCAD coverages that use polygons and lines to represent the various thematic attributes. The following coverages were created in this manner:

1. Biogeophysical attributes-

a) elevations - lines mark boundaries of areas with equal elevation;

b) streams - lines represent the location of the main tributaries and the main river in the drainage basin;

c) annual rainfall - polygons represent levels of annual rainfall in the drainage basin;

d) soil type - polygons represent general descriptions of soil fertility and organic matter;

e) vegetative cover - polygons represent various types of forest, wetlands, and agriculture;

2. human development attributes-

a) counties - polygons represent each county or municipality located within

the boundaries of the drainage basin (the associated database includes population density, agricultural production, estimates of fertilizer and pesticide use, and mineral production);

b) monitoring stations - map of the locations of water quality monitoring stations along tributaries from Ecopetrol and Intevep (1996) (the associated raw data included river discharge, salinity, nutrient load, and sediment load);

c) road network - the size and route of the principle roads in the drainage basin;

Determination of Watersheds

In order to evaluate the organization of the Catatumbo River drainage basin, the basin was divided into watersheds, or sub-basins. Two distinct watershed types were delineated: segment watersheds and stream-order watersheds, defined below. Segment watersheds were used to calculate geo-potential and chemical potential of rain and stream inflows. Stream-order watersheds were used to organize the spatial pattern of emergy in the drainage basin.

Segment watersheds

A segment watershed included the area draining only from the sides of the stream into the entire length of a stream-segment as shown in Figure 5. It did not include watershed area upstream of the segment (but see Stream-order watersheds below). The numbers within the segment watersheds are example reference numbers for identifying information in the data base associated with a

A) Segment watersheds

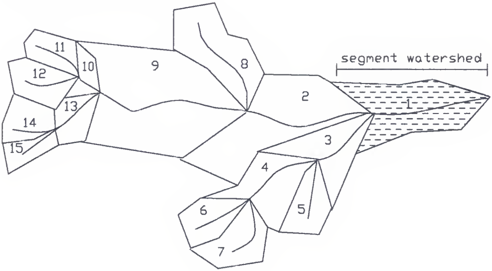
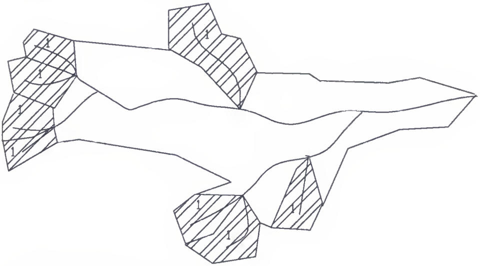
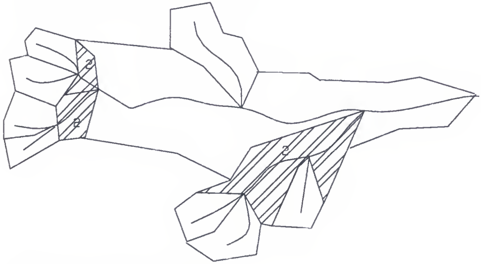


Figure 5. These four figures show how an imaginary drainage basin would be divided into segment watersheds and stream–order watersheds using the same methods as used in this study.
A) Segment watersheds were drawn around the drainage area for each individual stream segment. B) Stream–order watersheds were drawn by designating the drainage area of first–order segments as first–order watersheds. C) Second–order watersheds were drawn to include the drainage are of the second–order stream segments excluding the drainage area of first–order segments. D) shows the drainage area belonging to the third–order watershed, which excludes that of the other stream–order watersheds.

B) First-order watersheds



C) Second-order watersheds



D) Third-order watersheds

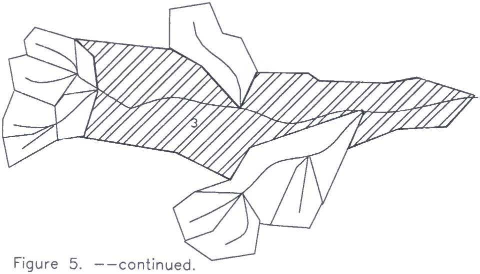


Figure 5. --continued.

particular watershed. The source of a stream-segment either began as a headwater source or followed immediately downstream of a convergence between other segments and extended to the next stream convergence. The area of a segment watershed was delineated from the elevation data provided by the elevation base map of the drainage basin (base map 1-a described above).

Stream-order watersheds

Stream-orders of the watersheds were assigned based on methods introduced by Strahler (1957). The lower end or mouth of the stream-order watershed was considered to be where the stream merged with another stream of the same order, at which point the order of the resultant stream increased by one. Stream-order watersheds included every smaller segment watershed that fell within it of lesser stream-order magnitude. For example, the area of a second-order watershed included any areas draining directly into it and areas of the first-order drainage basins whose streams discharged into it. The third-order watershed included any areas draining directly into it and the areas of the second-order and first-order streams that discharged into it, and so on.

Figure 5B-D illustrates how the drainage basins for stream-order 1-3 were determined. The numbers within the stream-order watershed refer to the order of the most downstream-segment within that watershed. The watershed of the highest stream-order included the entire drainage basin of the Catatumbo River.

Water Budget of Segment Watersheds

A generalized water budget was calculated for each segment watershed as delineated by the associated map of segment watersheds. A systems

diagram, in Figure 6, shows which flows were considered important in the water budget of the segment watersheds. Each flow in the water budget became a separate attribute of the segment. Attributes became part of a database that was associated with the map of segment watershed boundaries.

Annual rainfall was added to the database by electronically overlaying (or combining) the two maps together. An areally weighted average was used to adjust the annual rainfall for a segment watershed when one segment watershed intersected more than one rainfall polygon. The equation used to determine the areally weighted average was as follows:

Average rainfall in segment watershed i (Ri) = $\Sigma(Rsi*(asi/Ai))$ (1)

where

Rsi = rain over polygon s (resulting from overlay) located within segment watershed i
asi = area of polygon s located within segment watershed i
Ai = area of segment watershed i

A coverage of evapotranspiration was created from the elevation coverage using the Thornthwaite equation (Chow, 1964). Elevations were converted to monthly temperatures using a seasonal graph of temperature variation and summed to give annual evapotranspiration. The Thornthwaite equation is as follows:

Evapotranspiration at elevation e (ETe) = $16 * (10*Tm / I)^a$ (2)

where

Derivation of constants can be found in Chow (1964)
e = for specific elevation
Tm=mean monthly temperature for month m (C°)
I= local heat index = $\Sigma(Tm/5)^{1.514}$
m=months 1 to 12
a=(0.675 * I * 3 - 77.1 * I * 2 + 17,920 * I + 492,390) * 10E-6

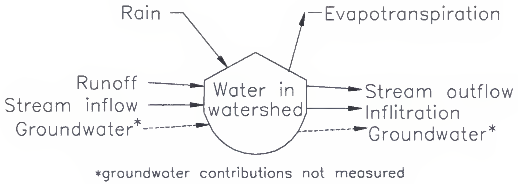


Figure 6. Water budget for segment watersheds of the Catatumbo drainage basin.

The sum of twelve months of evapotranspiration was used to estimate annual evapotranspiration for each elevation. Monthly temperature for the Catatumbo drainage basin was estimated by its relationship to elevation as given in Aguirre et al. (1989). This relationship is shown in Table 2.

The estimates of evapotranspiration were added to the database associated with the map of the drainage basin elevations. The map of elevations were electronically laid on top of (unioned to) the map segment watersheds. An areally weighted average (see equation (1) as an example) was used to determine the final estimate of evapotranspiration for each segment watershed.

Infiltration of rainfall into soils was estimated at 8% of rainfall (Romitelli, 1997) for segment watersheds in lowland areas (elevation drop less than 500 m/km) and nil for other watersheds. It was assumed that the inflow and outflow of groundwater in each segment watershed had no net change. Hence, runoff was calculated for each segment watershed as the difference between the rainfall and evapotranspiration coverages minus the estimate of infiltration.

Stream inflow was estimated as the runoff from all segment watersheds upstream. It was assumed that the volume of water flowing through a segment watershed was created by the convergence of runoff into the stream channel from within and flowing into that watershed. The estimates for stream flow were added to the database of water budget attributes for the segment watersheds.

Empower Density

By first converting the data in the base maps to empower, then overlaying certain base maps with the map of stream-order watersheds, new maps

Table 2. Seasonal temperature of watershed based on elevation.

Mean Elevation (above sea level)	Seasonal Temperature
0 – 25 m	27 - 31 C°
25-300 m	26 - 30 C°
300-500 m	25 - 29 C°
500-1000 m	18 - 22 C°
1000-2000 m	12 - 16 C°
2000 m	8 - 12 C°

empower were generated that were used in the spatial correlation analyses. Empower density was calculated by dividing the empower of a segment watershed or county (depending on the base map) by the area of the same watershed or county. The coverage of stream-order watersheds was combined with the map of empower density, then an areally weighted average was used to calculate empower for each stream-order watershed.

Final maps of empower density were made of renewable sources to the watersheds (available geo-potential and chemical potential, and geological inputs) and of indices of development. Indices of development empower density included the emergy used in the urban, agricultural, and mining sectors.

Maps of the various flows and storages of emergy were compared by visual inspection to determine any obvious spatial correlations. The population and principal road base maps were also compared to the other maps.

Graphs were made to determine if a general longitudinal trend or correlation between the river energies and development empower could be detected. The graphs were constructed to compare empower versus stream-order watershed. Graphs were also made of population density (using an areally weighted average) and road length (by summing total length) for each stream-order watershed.

Renewable sources of emergy flow to the segment watersheds

Geo-potential empower. The driving geopotential work, emergy of water, was calculated for each segment watershed. The database associated with the map of segment watersheds was used to determine the areas,

elevations, and water budget for each watershed. Final calculations of geo-potential empower were added to this database.

The emergy of both available geo-potential and used geo-potential was calculated following the methods of Rometelli (1997). Total water emergy flow, of geo-potential work within each segment was the sum of empower inflowing water and that empower of the runoff from within the segment watershed.

The used geo-potential of runoff was estimated using the water budget to each segment watershed. Runoff was estimated by multiplying one half of the change in each elevation of the segment watershed by the difference between rainfall minus evapotranspiration. The equation for the geo-potential of runoff was based on Odum (1996) as follows:

Geo-potential energy flow of runoff entering segment i
(J/yr) (Gri) = (Ri - ETi) * Ai * hi * r * g (3)

where

Ri = rain over segment watershed i (m/yr)
ETi = evapotranspiration over segment watershed i (m/yr)
Ai = area of segment watershed i (m^2)
hi = ½ change in elevation perpendicular to stream in segment watershed i (m)
r = density of water (1 E3 kg/m^3)
g = gravity (9.8 m/sec^2)

Geo-potential empower used in the stream-segment was determined by multiplying the geo-potential energy flow by the transformity for geo-potential energy in Appendix B.

The geo-potential energy of stream inflow to a segment watershed was calculated by multiplying the total volume of stream inflow by the difference in

inflow elevation and outflow elevation. The specific calculation for the geo-potential energy of stream inflow was based on Odum (1996) and is as follows:

Geo-potential energy of stream inflow entering segment i

(J/yr) (Gsi) = Si * di * r * g (4)

where

Si = stream inflow over segment watershed i (m^3/yr) (sum of all upstream runoff and infiltration)
di = change in elevation along river segment in watershed segment i (m)
r = density of water (1 E3 kg/m^3)
g = gravity (9.8 m/sec^2)

Geo-potential energy of stream inflow was multiplied by its transformity in Appendix B to calculate geo-potential empower of stream inflow.

The available empower contributing to any segment was the sum of all the geo-potential empower in the segments upstream from it. In this way, empower accumulated from headwater basins (with low stream-orders) to the mouth of the river. For segment watersheds with a stream-order of one (1), however, rain was the only source of geo-potential.

Chemical potential empower. Available chemical potential energy flow within each segment watershed was calculated as the sum of the chemical potential of water in rain and the chemical potential of water in stream inflow. The chemical potential energy used in each segment was calculated as the difference between the chemical potential energy flowing into a segment watershed and that flowing out of the same watershed.

Below is the general equation for the chemical potential of rain:

Chemical potential of rain in segment watershed i
(J/yr) (Cri) = Ri * Ai * G * r (5)

where

Ri = average rain over segment watershed i (m/yr)
Ai = area of segment watershed i (m^2)
G = Gibbs free energy between fresh and sea water (4940 J/kg)
r = density of water (1 E3 kg/m^3)

The volume of water evaluated for calculating the chemical potential of stream inflow was determined as the sum of the runoff (and infiltration) of all upstream watersheds (see calculation of geo-potential of stream inflow).

Gibbs free energy of water was estimated for stream inflow using known salinities. Salinity data from Intevep (1996), taken at the monitoring stations, were interpolated over segment watersheds by dividing measured salinties by the number of upstream watersheds contributing directly to it.

The closest measured quantity of salinity was multiplied by the ratio of the area of the watershed without a station to the total area of all the watersheds contributing to the monitoring station. Thus, the estimated concentration of salinty for each watershed without a monitoring station was adjusted using an areally weighted ratio so that larger watersheds would have proportionately higher concentrations. It was assumed that concentrations were additive, thus, the sum of upstream concentrations equaled that of the measured value. The equation used for determining Gibbs free energy relative to seawater (see Snoeyink and Jenkins, 1980) for the different watersheds was as follows:

Gibbs free energy (J/g) (G)= [(8.33 J/mole/deg)(300 °C)/(18 g/mole)]*

LN[1X10^6-Si)ppm/(965,000ppm)] (6)

where

Si=dissolved solids in water for segment watershed i (ppm)
965,000 ppm = salinty of seawater

Chemical potential energy used was determined as the difference between the chemical potential of the stream inflow and runoff (and infiltration) in a stream-segment and that of the chemical potential of the outflow of the same stream-segment. The equation is as follows:

Chemical potential energy (J/yr) (Cu) = Cet +[(Cis+Cir)-Cos] (7)

where

Cet = chemical potential energy flow of rain (J/yr)
Cis = chemical potential energy of inflow stream (J/yr)
Cir = chemical potential energy flow of runoff and infiltration (J/yr)
Cos = chemical potential energy of outflow stream (J/yr)

Chemical potential empower for each stream-segment was calculated by multiplying the chemical potential energy of the segment by the transformity for chemical potential of stream flow found in Appendix B.

Geological inputs. Geological inputs in the form of emergy were estimated for the different elevations of each segment watershed. The emergy input was calculated based on methods used by Romitelli (1997) and developed by Chorley et al. (1984), which used American and European drainage basins as empirical models. Final calculations were added to the database associated with the map of segment watersheds.

In order to calculate geological input to each segment watershed, an erosion rate was estimated for each mean elevation using the following equation:

Erosion rate for stream-segment i (m/1000 m) (Di)

$$= 0.0001535 \text{ mi} - 0.01088 \quad (8)$$

where

mi = mean elevation of stream-order watershed i (m)

The estimated weight of eroded rock entering each segment watershed was estimated by the multiplying the erosion rate by the area of the watershed and density of the rock found in the watershed. Rock density was based on a recommended density (Odum, 1996; Rometelli, 1997) of 2.6 ton/m^3 or 2.6 E6 g/m^3. The estimate of eroded rock was assumed to equal the weight of rock uplift from below ground.

The emergy flow of the geological input to each segment watershed was calculated by multiplying the rock eroded by the average global emergy per mass for the earth cycle (see Appendix B). The calculations of geological input were added to the map of elevations. This map was electronically overlaid onto the map of stream-order watersheds to calculate an areally weighted average used to estimate the geological input to each stream-order watershed.

Total renewable emergy flow to a stream-order watershed

The total emergy flow contribution to a segment watershed equaled the sum of the empower of geo- and chemical potentials of runoff and stream inflow, and the geological input of uplift and erosion. Hence, the total emergy flow contribution to a watershed included the sum of all renewable sources of empower. These flows were summed in the database associated with the map of segment watersheds. A final map of each flow was made by transferring the values of empower associated with each segment watershed to that the stream-order watershed in which it was a part. Where necessary, an areally weighted

average was used to determine the empower of each renewable source to a stream-order watershed.

Development empower

Indices of development empower included the empower generated in the urban, agricultural, and mining sectors. Figure 7 shows the flows of emergy included in these analyses. Empower was first calculated on a county basis, then the county map was overlaid on the map of stream-order watersheds. An areally weighted average was used to determine the empower for each of the stream-order watersheds.

Fuel use and goods and services in urban areas were taken from the emergy analyses at the national level and used as urban emergy flow estimates for the counties in the watershed. It was assumed that the empower in urban areas of each watershed was dependent on the average income earned in each county in which the watershed is located. In other words, counties with higher incomes had greater access to outside markets which could supply the county with materials, technology, and labor necessary for it to grow.

The data for the calculation of urban empower were derived from the national average consumption of resources determined in the emergy analysis section of this study. Each measure was adjusted by use of the income multiplier for the county and also multiplied by the population of the county. For example, if the income of a county equaled the national average income, then the index was multiplied by 1.0. If the county income was one-half (1/2) the national income, then the index was multiplied by 0.5. The index for a county whose income was

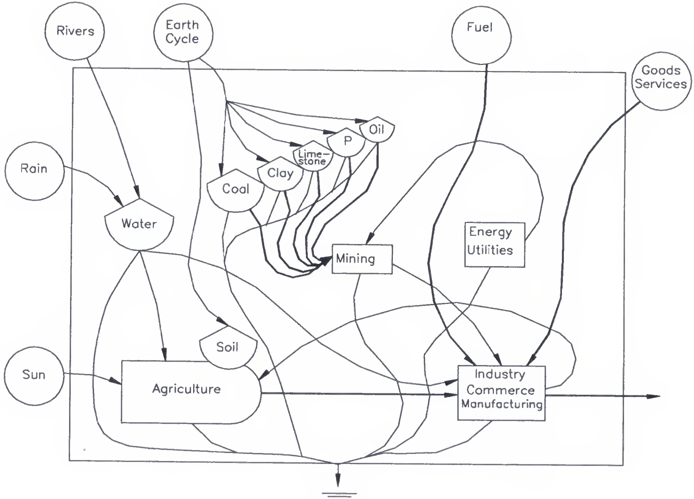


Figure 7. Systems diagram of development empower. Thicker lines are those flows analyzed in this study.

twice that of the national average would be multiplied by 2.0, etc. The data for the county income was taken from Aguirre et al. (1989).

For the agricultural sector, empower was calculated by evaluating crop production taken from Aguirre et al. (1989), which would include all the empower provided to this sector. Total production of agricultural crops was provided in tons. The production of each crop was multiplied by caloric values (see Appendix B) and then by transformities (see Appendix B) to determine emergy used in agricultural production.

The energy of fertlizers was estimated based on the average application rates for each crop. The information was taken from MARAVEN (1987) and personal communication with Ms. Zulay Rivas, Institute of the Conservation of Lake Maracaibo (ICLAM), Maracaibo, Venezuela. Application quantities (kilograms per hectare) where dervived by multiplying the reference estimate by the proportion of agricultural activity in each county in the watershed. Empower of fertilizers was determined by multiplying each fertilizer type (phosphorus and nitrogen based) by their transformities (see Appendix B) and adding the empower of each together.

The amount of pesticides was estimated based on the average application rates recommended by ICLAM. However, for this study pesticides were not distinguished by crop type, base chemicals, or target organism. Application quantities (in terms of energy per hectare) where estimated by taking the recommended application rate and multiplying it by the areally proportion of agricultural activity in each county in the watershed. Empower of pesticides was

determined by multiplying the energy flow of pesticides into the county its respective transformity (see Appendix B).

Empower in the mining sector was evaluated as that required for total production of the different minerals extracted. Mining production data came from Aguirre et al. (1989). The main substances being extraced include oil, coal, and clay. Data on a county basis were obtained from MARAVEN (1987) and Aguirre et al. (1989). Oil and coal production and clay extraction were converted into empower by multiplying the total mass by an appropriate transformity (see Appendix B) or emergy per mass (also called transmassity). Total mineral production empower was determined by summing the empower of oil, coal, and clay production.

Emergy of Storages

Emergy in a volume of river water in the stream-order watersheds was determined spatially by calculating the storage of environmental resources. Storages included the following: a) lowland rainforest; b) lower montane forest; c) montane forest (also known as piedmont); d) alpine forest; e) semi-desert; f) semi-desert g) swamp forest; h) soil organic matter; i) oil; j) coal; k) clay; l) limestone; and m) phosphorus rock. The calculations for determining the emergy in storages of resource reserves are provided in Table 3.

Emergy of Water

Emergy of water quality was determined per volume of river water (sej/m^3) and included the following constituents: a) total nitrogen; b) total phosphorus; c) river sediments, and d) oil. An estimate of the average chemical potential per m^3

Table 3. Equations for calculating emergy storage in the Catatumbo drainage basin.

1. Biomass in Forests =
(area of forest cover)*(biomass)*(4.78 kcal/g)*(4186 J/kcal)* (transformity)

forest cover	area (km^2)	biomass (tons/ha) (Brown and Lugo, 1984)
alpine forest	31	325
lower montane forest	3233	572.6
lowland tropical rainforest	4914	405.4
montane forest	1729	394.9
paramo	31	200
semi-desert	906	200
swamp forest	3382	4.012 kcal/ha

transformity = 40000 sej/J (Doherty and Brown,1993)

2. Organic Matter in Soil=
(organic matter content)*(5.4 kcal/g)*(4186 J/kcal)*(transformity)

soil type	organic matter content (g/m^2)
low organic matter/high fertility	450
low organic matter/low fertility	200
low organic matter/mixed fertility	350
rich organic matter/low fertility	700
rich organic matter/mixed fertility	600
stoney/high fertility	0

transformity = 62500 sej/j (Doherty and Brown, 1993)

Table 3. --continued.

3. Minerals and other
mining materials =

(empower density)*(minimum years mining left)

Material	Mininum mining years left
Oil	25
Coal	50
Clay	50
Limestone	50
Phosphorus	50

4. Total =

(biomass)+(organic matter)+(mining materials)

of river water was also calculated by dividing the average annual chemical potential for each order of watershed by the average annual discharge in the same watershed. In addition, an evaluation of the emergy per volume of the water itself, exclusive of the constituents, at the scale of the watershed was done for comparison to that of the emergy of water quality (emergy of the constituents per volume) at the scale of the river. Data from Ecopetrol and Intevep (1996) were used from specific site locations.

River-water quality data from Intevep (1996), taken at the upstream monitoring stations, were interpolated over segment watersheds where data were taken to those without sampling stations the same way as was done for estimating salinity.

The emergy per volume of the river water constituents and chemical potential were mapped, and compared with the location of development, population, and principal roads. In order to determine general correlations, graphs were constructed of average emergy for river-water quality per stream-order watershed.

Emergy of constituents in river water

The emergy per liter of each constituent (nitrogen, phosphorus, river sediments, and spilled oil) was calculated by multiplying the concentration (g/l) by the emergy per mass specific for that type of constituent at that concentration. Emergy per mass values are in Appendix B. Emergy per liter was then multiplied by 1000 liters per m^3 to determine emergy of each constituent per m^3 of river water.

Emergy of water at the scale of the watershed

A table was made between the emergy of water (exclusive of constituents) per volume of river water in a watershed, which includes the accumulation of the emergy of water as it flows downstream, to the emergy of water quality constituents per cubic meter of river water, in which the emergy of the water itself is excluded. Emergy per cubic meter of river water was calculated by dividing the geopotential emergy (sej/yr) per stream order by the average discharge (m^3/yr) for that stream order.

Transport ratio of emergy constituents in river water

The final index of the potential impact of development on longitudinal patterns of watershed resources was the use of the transport ratios of the river-water constituents. This ratio is the river water emergy required to carry a solar emjoule of material emergy through the stream system.

Transport ratios higher than one indicate that more geo-potential emergy is available than that of the constituent emergy it is carrying downstream. Lower transport ratios indicate that more emergy of a particular constituent at a certain place in the river can be carried downstream by relatively low available geo-potential emergy at that same place. Transport ratios approaching one (1) indicate the amount of constituent emergy being carried is reaching the same level of geo-potential emergy available.

If the same amount of constituent emergy is transported by a smaller amount of river water emergy, therefore a low transport ratio, then the transport process could be considered more efficient. On the other hand, low transport

ratios could also indicative of turbid or highly concentrated waters as the emergy of the constituents would be high compared to that of the water's geo-potential. This could mean that although more constituents are being carried by less energy, the river's ecosystems could be overloaded by the abundance of the constituents.

It was calculated by dividing the river geo-potential empower for the stream-order watersheds by the emergy of the constituent. In other words, the ratio compared the emergy of the carrier of the constituent to the emergy of the constituent itself. The following is the specific equation used:

Transport ratios of water at monitoring station m of constituent x

$$(Tmx) = Gm / Xm \tag{10}$$

where

Gm = geo-potential empower of river at monitoring station m (sej/yr)
Xm = emergy of constituent X at monitoring station m (sej)

RESULTS

The results of this study are presented in the same order as the methods. Provided are emergy analyses of the larger systems in which the Catatumbo drainage basin is a part and summaries of important emergy indices. Related maps are presented together. The final calculations of empower density, emergy storage, and emergy per volume in river water are summarized by stream-order watershed and presented in graphs.

Emergy Analyses

In this section, results relating to questions of the organization of the larger systems of which the Catatumbo drainage basin is a part. Each analysis includes a systems diagram, emergy analysis table, and the calculation of various overview indices.

Figure 9 shows a systems diagram of Venezuela. The country contains tropical forests, savannas, and coastal ecosystems, but the Lake Maracaibo ecosystem is prominent in size and its importance to the Venezuelan economy. The potential energies from rain and river flow are the largest of the renewable emergy flows of Venezuela as shown in Table 4. The chemical potential of rain reaches 1383.26E20 sej/yr (item 4), and the geo-potential of river flow approximates 493.87E20 sej/yr (item 8), which is almost totally from the Orinoco River.

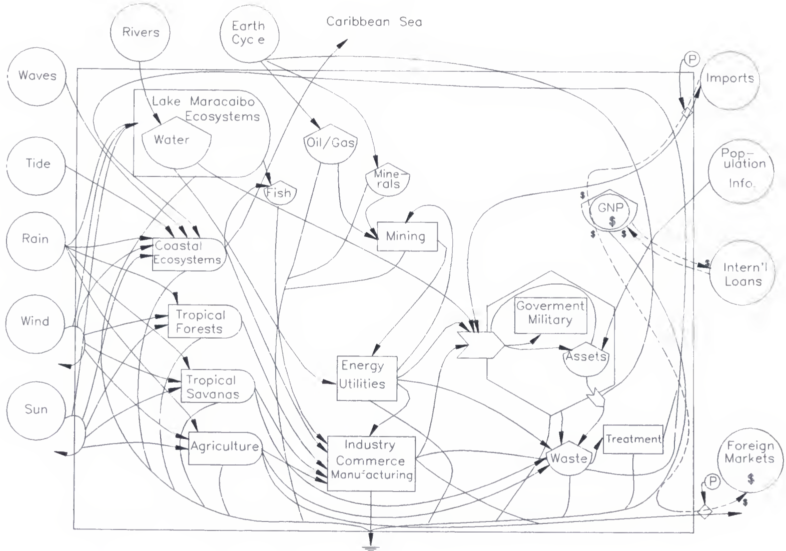


Figure 9. Systems diagram of Venezuela.

Table 4. Emergy analysis of Venezuela.

No.	Items	Energy		Transformity	Emergy	Emdollar
	Renewables	J/yr		Sej/unit	Sej/yr E20	Sej/$ E8
1	Sun	1.21E+21	J	1.00E+00	12.07	1.81
2	Earth cycle	9.12E+17	J	6.06E+03	55.22	8.29
3	Rain - chemical potential	8.98E+18	J	1.54E+04	1383.26	207.65
4	Rain - geopotential	2.77E+18	J	8.89E+03	245.77	36.89
5	Wind	2.90E+18	J	6.23E+02	18.07	2.71
6	Tide	3.06E+17	J	2.36E+04	72.17	10.83
7	Waves	3.47E+14	J	2.59E+04	0.09	0.01
8	River geopotential	5.56E+18	J	8.89E+03	493.87	74.14
	ndigenous Non-renewable Sources					
9	Agricultural production	1.78E+17	J	2.00E+05	355.57	53.38
10	Electricity	2.09E+17	J	1.59E+05	332.08	49.85
11	Livestock production	4.71E+16	J	2.00E+06	941.79	141.38
12	Fisheries	5.56E+15	J	2.00E+06	111.28	16.71
13	Forest Extraction	2.45E+15	J	1.87E+04	0.46	0.07
	Nonrewable sources from within system					
14	Natural gas	8.45E+17	J	4.80E+04	405.60	60.89
15	Crude oil	6.68E+17	J	5.30E+04	354.04	53.15
16	Phosphate fertilizers	3.93E+11	g	5.17E+09	20.32	3.05
17	Minerals	9.18E+12	g	9.20E+08	84.46	12.68
18	Crude steel	3.14E+09	g	2.64E+09	0.08	0.01
19	Iron ore	1.85E+14	J	6.01E+07	111.23	16.70
	Imports					
20	Oil deriv. prods.	4.95E+17	J	6.60E+04	326.70	49.04
21	Steel	8.80E+11	g	2.64E+09	23.23	3.49
22	Minerals	5.11E+12	g	9.20E+08	47.01	7.06
23	Agr. & forestry products	3.07E+16	J	2.00E+05	61.40	9.22
24	Livestock	1.12E+15	J	2.00E+06	22.40	3.36
25	Foods	8.12E+15	J	8.50E+04	6.90	1.04
26	Plastics & rubber	1.44E+15	J	6.60E+04	0.95	0.14
27	Chemicals	1.59E+12	g	3.80E+08	6.04	0.91
28	Wood, paper, etc.	8.55E+15	J	1.30E+06	111.15	16.69
29	Mech & trans. equipment	4.41E+11	g	6.70E+09	29.55	4.44
30	Services	1.10E+10	$	1.60E+12	176.00	26.42
31	Tourism	2.29E+09	$	1.60E+12	36.64	5.50

Table 4. --continued.

No.	Items	Energy		Transformity	Emergy	Emdollar
	Exports					
32	Cash crops	1.91E+15	J	2.00E+05	3.82	0.57
33	Fishery products	1.29E+15	J	2.00E+06	25.80	3.87
34	Livestock	1.95E+14	J	2.00E+06	3.90	0.59
35	Oil crude & derivatives	4.14E+18	J	6.00E+04	2484.00	372.89
36	Steel	1.80E+13	g	2.64E+09	475.20	71.34
37	Minerals	7.10E+12	g	9.20E+08	65.32	9.81
38	Chemicals	8.39E+11	g	3.80E+08	3.19	0.48
39	Service in exports	1.42E+10	$	6.66E+12	945.93	142.00
40	Tourist Service	2.00E+08	$	6.66E+12	13.32	2.00

Livestock production has the highest emergy flow of the indgenous nonrenewable sources (941.79E20 sej/yr, item 11). Agriculture (355.57E20 sej/yr, item 9) and electricity production (332.08E20 sej/yr, item 10) are approximatily equal flows in the Venezuela economy. Forest extraction is the smallest of these flows (0.46E20 sej/yr, item 13).

Oil is the main natural resource extracted in Venezuela. As a nonrenewable sources found within the system, crude oil (354.04E20 sej/yr) and natural gas (405.6 sej/yr) have the highest emergy flows, items 14 and 15. Oil is also the largest flow of emergy imported to Venezuela (oil dervived products, item 20, 326.7E20 sej/yr) and the largest flow of emergy exported from Venezuela (oil crude and derivatives, item 35, 2484.0E20 sej.yr).

The overview indices for Venezuela are given in Table 5. Renewable sources of emergy flows and that of indigenous nonrenewable sources are similar, 1.95E23 sej/yr and 1.74 sej/yr, respectively. The ratio of use of environmental sources of emergy flow to that in the economy is nearly 1:1 (index 9). Exports of emergy flow from Venezuela to other national economies is approximately 5 times that which is imported to Venezuela (index 11) creating a deficit of emergy due to trade of 3.21E23 sej/yr. More than half (59%) of the emergy used in the country is derived from home sources (rural and urban use) (index 14).

The current emergy use per unit area in Venezuela is 4.24E11 sej/m^2 (index 15) and that per person (given a current population estimate of 20.5 million people) of 1.88E16 sej/per (index 16). If the country's population had to

Table 5. Overview indices of annual solar emergy-use, origin, and economic and demographic relations for Venezuela, 1992.

	Name of Index	Derviation	Quantity	Unit
1	Renewable solar emergy flow (rain, tides, earth heat flows)	R	1.95E+23	sej/yr
2	Solar emergy flow from indigenous nonrewable reserves	N	1.74E+23	sej/yr
3	Flow of imported solar emergy	$F+G+P_2I$	811E+20	sej/yr
4	Total emergy flows	$R+N+F+G+P_2I$	4502E+20	sej/yr
5	Total emergy used, U	$R+N_0+N_1+F+G+P_2I$	3864E+20	sej/yr
6	Economic component	U-R	1914E+20	sej/yr
7	Total exported solar emergy	N_2+B+P_1E	4020E+20	sej/yr
8	Percent locally renewable (free)	R/U	50.45	%
9	Economic/environment ratio	(U-R)/R	0.98	
10	Ratio of imports to exports	$(F+G+P_2I)/(N_2+B+P_1E)$	0.20	
11	Ratio of exports to imports	$(N_2+B+P_1E)/(F+G+P_2I)$	4.96	
12	New solar emergy deficit due to trade (imports minus exports)	$(F+G+P_2I)-(N_2+B+P_1E)$	-3.21E+23	sej/yr
13	% solar emergy-use purchased	$(F+G+P_2I)/U$	21.00	%
14	% solar emergy-use derived from home sources	$(N_0+N_1+R)/U$	5.90E+01	%
15	Solar emergy-use per unit area (9.12E11 m^2)	U/area	4.24E+11	sej/m^2
16	Solar emergy-use per person (20.5 million people)	U/population	1.88E+16	sej/per.
17	Renewable carrying capacity at present living standard	(R/U)*population	1.03E+07	people
18	Developed carrying capacity at same living standard	8*(R/U)*population	8.27E+07	people
19	Solar emergy-use to GDP	$P_1=U/GDP_{1992}$	6.66E+12	sej/$
20	% Electric	(electrical use)/U	8.59	%
21	% Fossil fuels	(fuel use)/U	19.66	%
22	Fuel-use per person	(fuel use)/population	3.71E+15	sej/per.

depend on only those emergy flows from renewable sources, then the population should not exceed 10.7 million people (index 17). However, if all the renewable and nonrenewable sources were used at their capacity with no change in emergy per person, then the population could grow up to 83 million people (index 18). The emdollar or emergy use to the Venezuelan GDP for the current economy is estimated at 6.66E12 sej/US$ (index 19). Fuel use by the country is approximately 20% of the total emergy used (index 21) or 3.71E15 sej of fuel use per person (index 22).

The Colombian system is shown in Figure 10, and is very similar to that of Venezuela with the exception of not having an equivalent ecosystem as Lake Maracaibo. Emergy flows in rain are the largest renewable sources to Colombia as shown in Table 6. The emergy flow of chemical potential in rain is 1361.01E20 sej/yr (item 3), and the geo-potential of rain is 497.6E20 sej/yr (item 4).

Agricultural production (435.64E20 sej/yr, item 9) is a larger emergy flow within Colombia and than Venezuela. However, livestock production (275.7E20 sej/yr, item 11), electricity production (198.2E20 sej/yr, item 10), and fisheries (33.86E20 sej/yr, item 12) are much smaller flows of indigenous nonrenewable sources in Colombia.

Oil is also prominent in the Colombian economy as both an import emergy flow (498.2E20 sej/yr, item 20) and as an export emergy flow (1266E20 sej/yr, item35). Although a lot of energy is invested in cash crops (item 32), the emergy

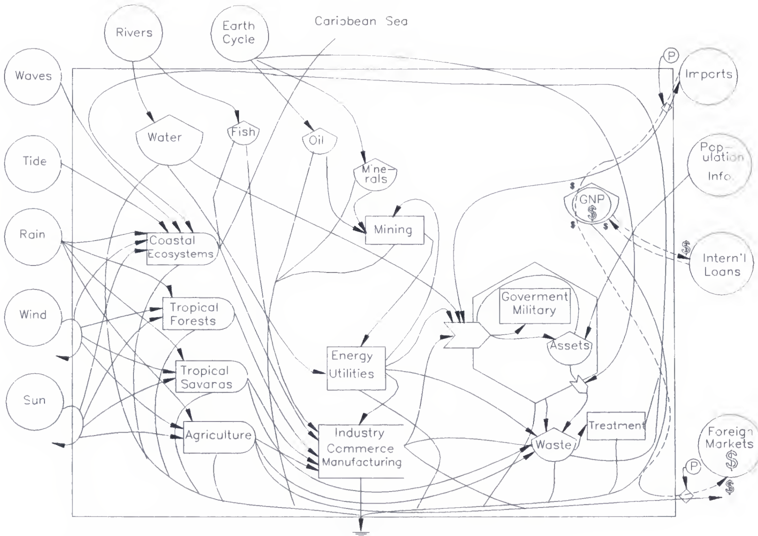


Figure 1C. Systems diagram of Colombia.

Table 6. Emergy analysis of Colombia.

No.	Items	Energy		Transformity	Emergy	Emdollar
	Renewables	J/yr		Sej/unit	Sej/yr E20	Sej/$ E8
1	Sun	1.17E+21	J	1.00E+00	11.68	1.38
2	Earth cycle	1.04E+18	J	6.06E+03	62.89	7.45
3	Rain - chemical potential	8.84E+18	J	1.54E+04	1361.01	161.12
4	Rain - geopotential	5.60E+18	J	8.89E+03	497.60	58.91
5	Wind	2.90E+18	J	6.23E+02	18.07	2.14
6	Tide	3.67E+17	J	2.36E+04	86.71	10.26
7	Waves	3.10E+17	J	2.59E+04	80.24	9.50
8	River geopotential	1.54E+18	J	8.89E+03	137.19	16.24
	Indigenous Non-renewable Sources					
9	Agricultural production	2.18E+17	J	2.00E+05	435.64	51.57
10	Electricity	1.25E+17	J	1.59E+05	198.20	23.46
11	Livestock production	1.38E+16	J	2.00E+06	275.70	32.64
12	Fisheries	1.69E+15	J	2.00E+06	33.86	4.01
13	Forest Extraction	5.43E+15	J	1.87E+04	1.02	0.12
	Nonrewable sources from within system					
14	Natural gas	8.65E+16	J	4.80E+04	41.53	4.92
15	Crude oil	4.30E+17	J	5.30E+04	227.87	26.98
16	Phosphate fertilizers	4.39E+11	g	5.17E+09	22.68	2.68
17	Minerals	7.03E+09	g	9.20E+08	0.06	0.01
18	Crude steel	7.33E+11	g	2.64E+09	19.35	2.29
19	Iron ore	3.71E+12	J	6.01E+07	2.23	0.26
	Imports					
20	Oil deriv. prods.	7.55E+17	J	6.60E+04	498.20	58.98
21	Steel	1.01E+11	g	2.64E+09	2.67	0.32
22	Minerals	1.12E+12	g	9.20E+08	10.30	1.22
23	Agr. & forestry products	5.34E+15	J	2.00E+05	10.68	1.26
24	Livestock	9.00E+14	J	2.00E+06	18.00	2.13
25	Foods	7.00E+15	J	8.50E+04	5.95	0.70
26	Plastics & rubber	2.31E+15	J	6.60E+04	1.53	0.18
27	Chemicals	1.59E+12	g	3.80E+08	6.04	0.72
28	Wood, paper, etc.	1.00E+16	J	1.30E+06	130.00	15.39
29	Mech & trans. equipment	3.43E+11	g	6.70E+09	22.98	2.72
30	Services	9.87E+09	$	1.60E+12	157.92	18.69
31	Tourism	7.45E+09	$	1.60E+12	119.20	14.11
	Exports					
32	Cash crops	3.43E+15	J	2.00E+05	6.86	0.81
33	Fishery products	9.00E+14	J	2.00E+06	18.00	2.13

Table 6. --continued.

No.	Items	Energy		Transformity	Emergy	Emdollar
34	Livestock	3.23E+14	J	2.00E+06	6.46	0.76
35	Oil crude & derivatives	2.11E+18	J	6.00E+04	1266.00	149.87
36	Steel	8.45E+12	g	2.64E+09	223.08	26.41
37	Minerals	1.78E+13	g	9.20E+08	163.76	19.39
38	Chemicals	1.07E+12	g	3.80E+08	4.05	0.48
39	Service in exports	2.63E+09	$	8.45E+12	222.42	26.33
40	Tourist Service	5.15E+08	$	8.45E+12	43.50	5.15

flow of their export (6.86E20 sej/yr) is relatively minor compared with oil, steel (223.08E20 sej/yr, item 36) and minerals (163.76E20 sej/yr, item37).

The overview indices of emergy for Colombia are provided in Table 7. Renewable sources of emergy flow to Colombia (1.58E23 sej/yr, index 1) are slightly higher than that from indigenous nonrenewable sources (9.44E22 sej/yr, index 2). Of the total emergy flows (3394E20 sej/yr, index 4), almost all is used by the country (3143E20 sej/yr, index 5). Like Venezuela, the ratio of the economic component of the total emergy used to environmental component is approximately 1:1 (index 9). Colombian exports are only twice that of their imports (index 11); however, that trade imbalance still gives them a emergy deficit of 1.09E23 sej/yr (index 12).

The emergy use per unit area in Colombia is 3.03E11 sej/m2 (index 15). The emergy use per person, given a current population of 33 million people, is 9.35E15 sej/per (index 16) which is less than that for Venezuela. If the population had to depend on only the renewable sources of emergy flow, then the carry capacity of the country should not exceed 16 million people (index 17). However, if both the renewable and nonrenewable sources were used to their maximum potential without compromise to the current emergy per person living standard, then the population could grow to 133 million people (index 18).

The emdollar of Colombia at the current GDP is 8.45E12 sej/US$ (index 19), or approximately 2E12 sej/US$ higher than that for Venezuela. Only 8.5% of the emergy use is from fossil fuel consumption (index 21) resulting in an average of 8.17E14 sej/yr emergy fuel use per person (index 22).

Table 7. Overview indices of annual solar emergy-use, origin, and economic and demographic relations for Colombia, 1992.

	Name of Index	Derviation	Quantity	Unit
1	Renewable solar emergy flow (rain, tides, earth heat flows)	R	1.58E+23	sej/yr
2	Solar emergy flow from indigenous nonrewable reserves	N	9.44E+22	sej/yr
3	Flow of imported solar emergy	$F+G+P_2I$	864E+20	sej/yr
4	Total emergy flows	$R+N+F+G+P_2I$	3394E+20	sej/yr
5	Total emergy used, U	$R+N_0+N_1+F+G+P_2I$	3143E+20	sej/yr
6	Economic component	U-R	1558E+20	sej/yr
7	Total exported solar emergy	N_2+B+P_1E	1954E+20	sej/yr
8	Percent locally renewable (free)	R/U	50.42	%
9	Economic/environment ratio	(U-R)/R	0.98	
10	Ratio of imports to exports	$(F+G+P_2I)/(N_2+B+P_1E)$	0.44	
11	Ratio of exports to imports	$(N_2+B+P_1E)/(F+G+P_2I)$	2.26	
12	New solar emergy deficit due to trade (imports minus exports)	$(F+G+P_2I)-(N_2+B+P_1E)$	-1.09E+23	sej/yr
13	% solar emergy-use purchased	$(F+G+P_2I)/U$	27.50	%
14	% solar emergy-use derived from home sources	$(N_0+N_1+R)/U$	5.67E+01	%
15	Solar emergy-use per unit area ($1.04E12\ m^2$)	U/area	3.03E+11	sej/m^2
16	Solar emergy-use per person (33.0 million people)	U/population	3.03E+17 9.53E+15	sej/km^2 sej/per.
17	Renewable carrying capacity at present living standard	(R/U)*population	1.66E+07	people
18	Developed carrying capacity at same living standard	8*(R/U)*population	1.33E+08	people
19	Solar emergy-use to GDP	$P_1=U/GDP_{1992}$	8.45E+12	sej/$
20	% Electric	(electrical use)/U	6.31	%
21	% Fossil fuels	(fuel use)/U	8.57	%
22	Fuel-use per person	(fuel use)/population	8.17E+14	sej/per.

The state of Zulia in Venezuela can be easily compared as a microcosm of the entire country geographically and economically as illustrated in the systems diagram in Figure 11. The difference is that Zulian markets generally go through the national economy before being dispersed outside the country.

Emergy flows in Zulia are summarized in Table 8. River geo-potential is the largest source of renewable emergy flow in this state (219E20 sej/yr, item 8). Agricultural production (60.8E20 sej/yr, item 9) and fisheries (66.77E20 sej/yr, item 12) are the largest flows of indigenous nonrenewable emergy flows.

Zulia is where much of the oil and gas drilling in Venezuela are concentrated which is why the oil exports are so high contributing over half of the oil exports from the entire country (1817E20 sej/yr, item 32).

Overview indices of emergy flows in Zulia are summarized in Table 9. The renewable emergy flows to Zulia (2.66E22 sej/yr, index 1) are nearly twice that of the indigenous nonrenewable sources (1.5E22 sej/yr, index 2). The ratio of the economic component of the total emergy used to that of the environmental component is 1.13:1 (index 9), which means there is less environmental resources being used than resources produced by the economy. Exported emergy flows of Zulia are over ten times that of imported emergy flows (index 11) creating an emergy trade deficit of 2.29E23 sej/yr (index 12).

The emergy use per unit area in Zulia is 1.13E12 sej/m^2 (index 15), which is 6E12 sej/m^2 higher than that for Venezuela. Emergy per per person is 3.10E16 sej/per (index 16) given a current population of 1.83 million, or almost

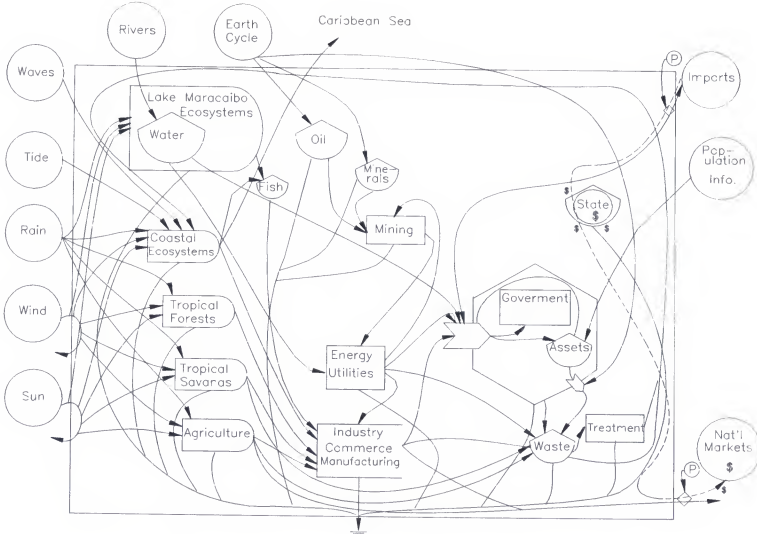


Figure 11. Systems diagram of Zulia.

Table 8. Emergy analysis of Zulia.

No.	Items	Energy		Transformity	Emergy	Emdollar
	Renewables	J/yr		Sej/unit	Sej/yr E20	Sej/$ E8
1	Sun	8.02E+19	J	1.00E+00	0.80	0.12
2	Earth cycle	5.02E+16	J	6.06E+03	3.04	0.47
3	Rain - chemical potential	2.92E+17	J	1.54E+04	44.94	6.92
4	Rain - geopotential	8.31E+16	J	8.89E+03	7.38	1.14
5	Wind	2.90E+18	J	6.23E+02	18.07	2.78
6	Tide	4.80E+15	J	2.36E+04	1.13	0.17
7	Waves	1.25E+13	J	2.59E+04	0.00	0.00
8	River geopotential	2.47E+18	J	8.89E+03	219.70	33.81
	Indigenous Non-renewable Sources					
9	Agricultural production	3.04E+16	J	2.00E+05	60.80	9.36
10	Electricity	1.37E+16	J	1.59E+05	21.85	3.36
11	Livestock production	2.83E+12	J	2.00E+06	0.06	0.01
12	Fisheries	3.34E+15	J	2.00E+06	66.77	10.28
13	Forest Extraction	2.25E+14	J	1.87E+04	0.04	0.01
	Nonrewable sources from within system					
14	Natural gas	3.78E+15	J	4.80E+04	1.81	0.28
15	Crude oil	9.62E+16	J	5.30E+04	50.98	7.85
16	Minerals	8.75E+11	g	9.20E+08	8.05	1.24
	Imports					
17	Oil deriv. prods.	1.48E+17	J	6.60E+04	97.98	15.08
18	Steel	2.64E+11	g	2.64E+09	6.97	1.07
19	Minerals	1.53E+12	g	9.20E+08	14.10	2.17
20	Agr. & forestry products	9.20E+15	J	2.00E+05	18.40	2.83
21	Livestock	3.35E+14	J	2.00E+06	6.70	1.03
22	Foods	2.44E+15	J	8.50E+04	2.08	0.32
23	Plastics & rubber	4.31E+14	J	6.60E+04	0.28	0.04
24	Chemicals	4.77E+11	g	3.80E+08	1.81	0.28
25	Wood, paper, etc.	2.57E+15	J	1.30E+06	33.35	5.13
26	Mech & trans. equipment	1.32E+11	g	6.70E+09	8.86	1.36
27	Services	3.30E+09	$	1.60E+12	52.80	8.13
28	Tourism	2.29E+08	$	1.60E+12	3.66	0.56
	Exports					
29	Cash crops	1.91E+15	J	2.00E+05	3.82	0.59
30	Fishery products	9.03E+14	J	2.00E+06	18.05	2.78
31	Livestock	1.37E+14	J	2.00E+06	2.73	0.42
32	Oil crude & derivatives	3.03E+18	J	6.00E+04	1817.31	279.68

Table 8. --continuted.

No.	Items	Energy		Transformity	Emergy	Emdollar
33	Minerals	4.97E+12	g	9.20E+08	45.72	7.04
34	Chemicals	5.87E+11	g	3.80E+08	2.23	0.34
35	Service in exports	9.94E+09	$	6.50E+12	645.87	99.40
36	Tourist Service	2.00E+07	$	6.50E+12	1.30	0.20

Table 9. Overview indices of annual solar emergy-use, origin, and economic and demographic relations for Zulia, 1992.

	Name of Index	Derviation	Quantity	Unit
1	Renewable solar emergy flow (rain, tides, earth heat flows)	R	2.66E+22	sej/yr
2	Solar emergy flow from indigenous nonrewable reserves	N	1.50E+22	sej/yr
3	Flow of imported solar emergy	$F+G+P_2I$	243E+20	sej/yr
4	Total emergy flows	$R+N+F+G+P_2I$	659E+20	sej/yr
5	Total emergy used, U	$R+N_0+N_1+F+G+P_2I$	565E+20	sej/yr
6	Economic component	U-R	300E+20	sej/yr
7	Total exported solar emergy	N_2+B+P_1E	2537E+20	sej/yr
8	Percent locally renewable (free)	R/U	47.01	%
9	Economic/environment ratio	(U-R)/R	1.13	
10	Ratio of imports to exports	$(F+G+P_2I)/(N_2+B+P_1E)$	0.10	
11	Ratio of exports to imports	$(N_2+B+P_1E)/(F+G+P_2I)$	10.43	
12	New solar emergy deficit due to trade (imports minus exports)	$(F+G+P_2I)-(N_2+B+P_1E)$	-2.29E+23	sej/yr
13	% solar emergy-use purchased	$(F+G+P_2I)/U$	43.05	%
14	% solar emergy-use derived from home sources	$(N_0+N_1+R)/U$	5.09E+01	%
15	Solar emergy-use per unit area (5.02E10 m^2)	U/area	1.13E+12	sej/m^2
16	Solar emergy-use per person (1.83 million people)	U/population	3.10E+16	sej/per.
17	Renewable carrying capacity at present living standard	(R/U)*population	8.58E+05	people
18	Developed carrying capacity at same living standard	8*(R/U)*population	6.86E+06	people
19	Solar emergy-use to GDP	$P_1=U/GDP_{1992}$	6.50E+12	sej/$
20	% Electric	(electrical use)/U	3.86	%
21	% Fossil fuels	(fuel use)/U	9.34	%
22	Fuel-use per person	(fuel use)/population	2.58E+14	sej/per.

twice that for Venezuela. If the population of Zulia had to depend only on renewable emergy flows then the population should not exceed 858,000 people. However, if all resources were developed with little effect on the current emergy per person standard of living, then the population could increase to 6.8 million people.

Fuel use in Zulia is much less than that of the country. The percentage of fuel use in the total emergy use is 9.3% (index 21) and 2.58E14 sej/per (index 22). An estimate of the emergy use to GDP of Zulia is 6.5E12 sej/US$ (index 19), or approximately equal to that of the country.

Norte de Santander, Colombia is diagrammed in Figure 12. Its largest ecosystem is the Catatumbo watershed which takes up approximately three-fourths of the state. Other watersheds include a small section of the Orinoco River watershed that is not shown in the diagram.

The emergy analysis of Norte de Santander is given in Table 10. The geo-potential of rain (21.74E20 sej/yr, item 3) and river flow (18.06E20 sej/yr, item 6) are the largest sources of emergy flow in this State.

Agricultural production is the dominant source of indigenous nonrenewable sources (9.3E20 sej/yr, item 7). Tourism brings in the largest flow of imported emergy (596E18 sej/yr, item 23). Relative to the other flows, oil also is both a large import (498.3E18 sej/yr, item 14) and export (1266E18 sej/yr, item 25) in terms of emergy. However, the economy is also dependent on cash crops (651.51E18 sej/yr, item 24).

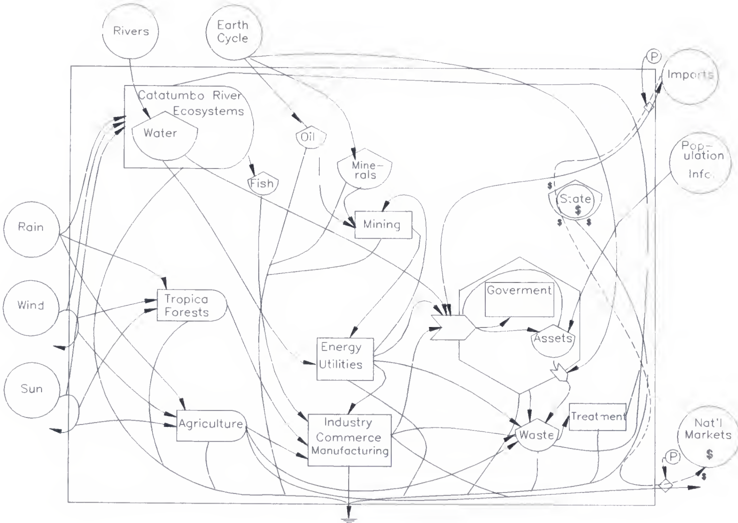


Figure 12. Systems diagram of Norte de Santander.

Table 10. Emergy analysis of Norte de Santander.

No.	Items	Energy		Transformity	Emergy	Emdollar
	Renewables	J/yr		Sej/unit	Sej/yr E18	Sej/$ E5
1	Sun	3.51E+19	J	1.00E+00	35.09	8.06
2	Earth cycle	2.72E+16	J	6.06E+03	164.80	37.84
3	Rain - chemical potential	1.41E+17	J	1.54E+04	2174.09	499.14
4	Rain - geopotential	6.00E+16	J	8.89E+03	533.40	122.46
5	Wind	2.90E+18	J	6.23E+02	1806.70	414.79
6	River geopotential	7.64E+15	J	8.89E+03	67.87	15.58
	Indigenous Non-renewable Sources					
7	Agricultural production	4.65E+15	J	2.00E+05	930.72	213.68
8	Electricity	6.25E+11	J	1.59E+05	0.10	0.02
	Nonrewable sources from within system					0.01
9	Natural gas	8.20E+11	J	4.80E+04	0.04	52.32
10	Crude oil	4.30E+15	J	5.30E+04	227.90	5.21
11	Phosphate fertilizers	4.39E+09	g	5.17E+09	22.68	1.48
12	Minerals	7.03E+09	g	9.20E+08	6.47	0.00
13	Iron ore	1.31E+02	J	6.01E+07	0.00	0.00
	Imports					
14	Oil deriv. prods.	7.55E+15	J	6.60E+04	498.30	114.40
15	Agr. & forestry products	5.34E+13	J	2.00E+05	10.68	2.45
16	Livestock	9.00E+12	J	2.00E+06	18.00	4.13
17	Foods	7.00E+13	J	8.50E+04	5.95	1.37
18	Plastics & rubber	2.31E+13	J	6.60E+04	1.52	0.35
19	Chemicals	1.59E+10	g	3.80E+08	6.04	1.39
20	Wood, paper, etc.	1.00E+14	J	1.30E+06	130.00	29.85
21	Mech & trans. equipment	3.43E+09	g	6.70E+09	22.98	5.28
22	Services	9.87E+07	$	1.60E+12	157.92	36.26
23	Tourism	3.73E+08	$	1.60E+12	596.00	136.83
	Exports					
24	Cash crops	3.26E+15	J	2.00E+05	651.51	149.58
25	Oil crude & derivatives	2.11E+16	J	6.00E+04	1266.00	290.66
26	Minerals	4.92E+09	g	9.20E+08	4.53	1.04
27	Chemicals	4.92E+09	g	3.80E+08	1.87	0.43
28	Service in exports	2.63E+07	$	4.36E+13	1145.54	263.00
29	Tourist Service	5.15E+06	$	4.36E+13	224.32	51.50

The overview indices of emergy are given in Table 11. The emergy flows to Norte de Santander from renewable sources (2.24E21 sej/yr, index 1) are almost three times that from indigenous nonrenewable flows (9.3E20 sej/yr, index 2). Most of the total emergy flows (40E20 sej/yr, index 3) are used (38E20 sej/yr, index 4).

The ratio of the economic component of total emergy used to that of the environmental component is 0.69:1 (index 9), which means that more environmental sources are used. The emergy flows being exported from Norte de Santander are almost four times (index 11) that being imported resulting in an emergy trade deficit of 2.44E21 sej/yr (index 12).

The emergy use per unit area in this State is 1.39E11 sej/m^2 (index 15), which about a third of that for Colombia. Given a current population of 890,000 people, the emergy per person living standard is 4.29E15 sej/per (index 16) or half that of the entire country. If the population had to depend only on renewable sources of emergy, then the population should not exceed 523,000 people (index 17). If all resources were developed without compromise to the current living standard, then the population could increase to 4.2 million.

Based on the economy of Norte de Santander, the emergy use to GDP is 4.36E13 sej/US$ (index 19), which is over five times that of the Colombia. Fuel use in this State is low relative to total emergy use at only 6% (index 21), but high relative to the population 1.25E15 sej/per (index 22).

A systems diagram of the Catatumbo drainage basin is presented in Figure 13. The drainage basin is divided into three sections. The first depicts

Table 11. Overview indices of annual solar emergy-use, origin, and economic and demographic relations for Norte de Santander, 1992.

	Name of Index	Derviation	Quantity	Unit
1	Renewable solar emergy flow (rain, tides, earth heat flows)	R	2.24E+21	sej/yr
2	Solar emergy flow from indigenous nonrewable reserves	N	9.31E+20	sej/yr
3	Flow of imported solar emergy	$F+G+P_2I$	9E+20	sej/yr
4	Total emergy flows	$R+N+F+G+P_2I$	40E+20	sej/yr
5	Total emergy used, U	$R+N_0+N_1+F+G+P_2I$	38E+20	sej/yr
6	Economic component	U-R	16E+20	sej/yr
7	Total exported solar emergy	N_2+B+P_1E	33E+20	sej/yr
8	Percent locally renewable (free)	R/U	59.12	%
9	Economic/environment ratio	(U-R)/R	0.69	
10	Ratio of imports to exports	$(F+G+P_2I)/(N_2+B+P_1E)$	0.26	
11	Ratio of exports to imports	$(N_2+B+P_1E)/(F+G+P_2I)$	3.87	
12	New solar emergy deficit due to trade (imports minus exports)	$(F+G+P_2I)-(N_2+B+P_1E)$	-2.44E+21	sej/yr
13	% solar emergy-use purchased	$(F+G+P_2I)/U$	22.45	%
14	% solar emergy-use derived from home sources	$(N_0+N_1+R)/U$	5.91E+01	%
15	Solar emergy-use per unit area (2.72E10 m^2)	U/area	1.39E+11	sej/m^2
16	Solar emergy-use per person (888,884 people)	U/population	4.29E+15	sej/per.
17	Renewable carrying capacity at present living standard	(R/U)*population	5.23E+05	people
18	Developed carrying capacity at same living standard	8*(R/U)*population	4.18E+06	people
19	Solar emergy-use to GDP	$P_1=U/GDP_{1992}$	4.36E+13	sej/$
20	% Electric	(electrical use)/U	0.00	%
21	% Fossil fuels	(fuel use)/U	6.01	%
22	Fuel-use per person	(fuel use)/population	1.25E+15	sej/per.

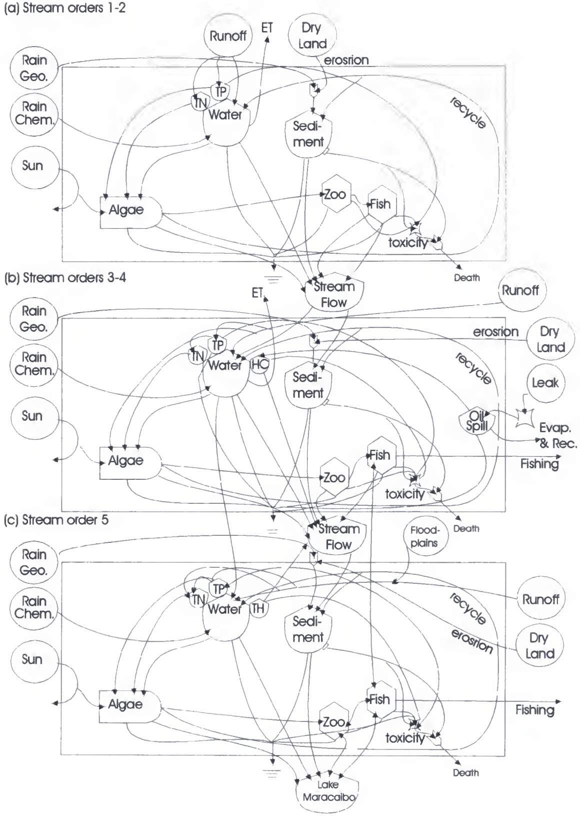


Figure 13. Systems diagram of the Catatumbo River drainage basin.

the general characteristics of the first and second-order stream watersheds. Although not analyzed, algae production and biota are shown to depict how they might be affected by water quality. The next section represents the changes that occur in the basin in the third and fourth stream-order watersheds including the occurance of oil spills. The final section shows the fifth-order watershed and its connections the Catatumbo River floodplains and Lake Maracaibo. Fish are shown to migrate back and fourth from the Lake up to the third stream-orders as discovered by Mojica (1992). The emergy analysis of the drainage basin was done spatially; the results are given in the following sections.

Spatial Analyses

Base Maps

The initial maps created for this study are presented in this section beginning with the biogeophysical attributes, followed by the cultural and development flow attributes.

The biogeophysical attributes of the drainage basin are first described by the average elevations of the Catatumbo drainage basin shown in Figure 14. Elevations in the basin range from sea level near Lake Maracaibo to over 3000 meters in the upper watersheds.

The streams of the Catatumbo drainage basin are shown in Figure 15. The largest tributaries are labeled, which include the Zulia River, Oro River, Tarra River, and the Pampalona. Tres Bocas is not a river, but rather a junction point of three rivers that combine to form the Tarra river.

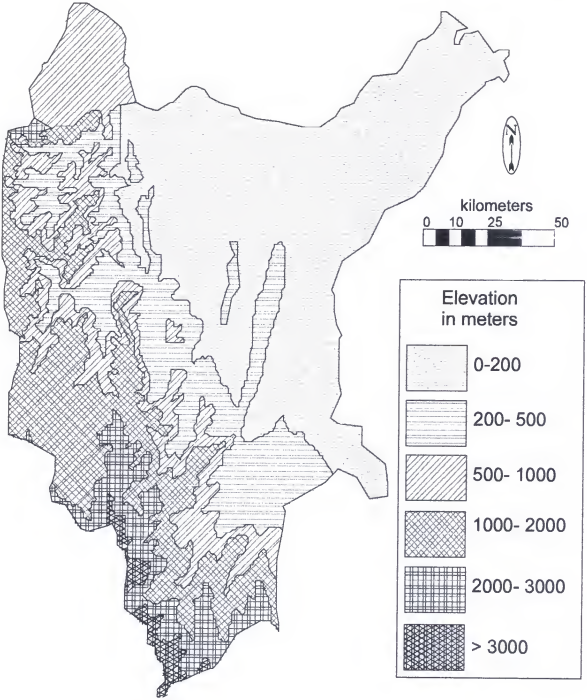


Figure 14. Elevations (relative to sea level) of the Catatumbo River drainage basin.

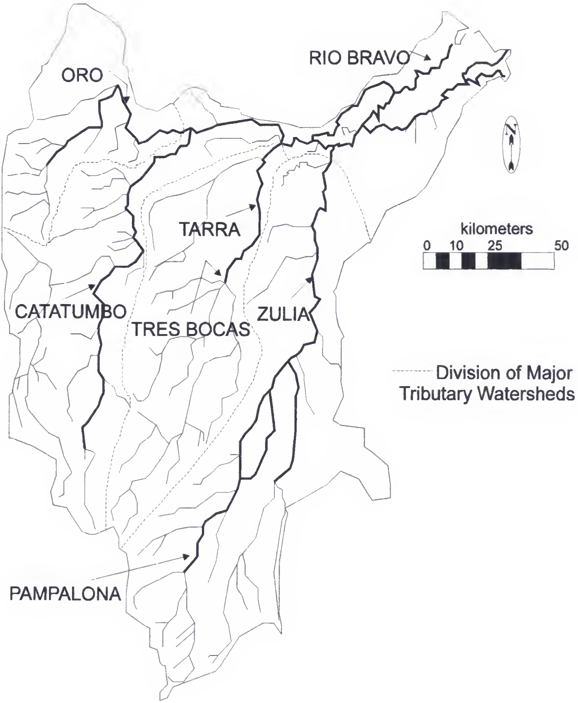


Figure 15. Streams of the Catatumbo River drainage basin. Main stream channels are in bold. Outline of major tributary watersheds are also shown.

Annual rainfall in the drainage basin is shown in Figure 16. Rainfall varies greatly in the basin ranging from semi-desert conditions (> 600 mm/yr) to rainforest (<2800 mm/yr). The largest amount of rain occurs in the mid-reaches of the drainage basin near the border between Venezuela and Colombia.

The distribution of major soil types in the Catatumbo drainage basin is provided in Figure 17. In the upper watersheds, soils range from low organic matter content and low fertility to rich organic matter content and high fertility. The lower watersheds are dominanted by soils rich in organic matter, but low fertility.

In Figure 18, the dominant land cover in terms of vegetation are shown. Much of the upper to mid-reach watersheds are either dominated by agriculture or montane forest. Two small areas in the higher altitudes of the drainage basin are covered by alpine forest and paramo vegetation. A relatively larger area is considered to be semi-desert. The lower watersheds of the basin are either lowland tropical forest or wetlands.

To describe the cultural aspects of the Catatumbo drainage basin, the basin's counties, population density of the drainage basin, and principle road network are provided in Figures 19, 20, and 21, respectively. In Figure 19, The Venezuelan county called Catatumbo was divided into smaller sections to increase its resolution relative to the Colombian countys. The sections were based on local divisions of city and municipality divisions. The raw data used for agricultural production, fertilizer and pesticide use, and mineral production was obtained on a per county basis and is provided in Tables 12-14.

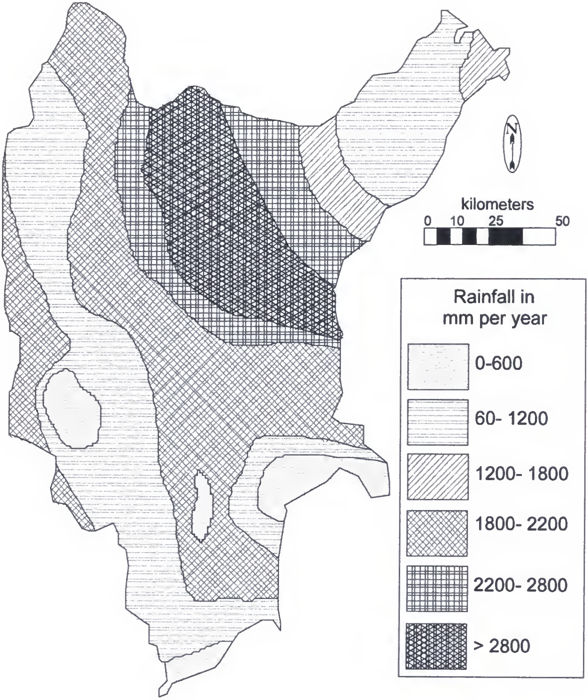


Figure 16. Annual rainfall in the Catatumbo River drainage basin.

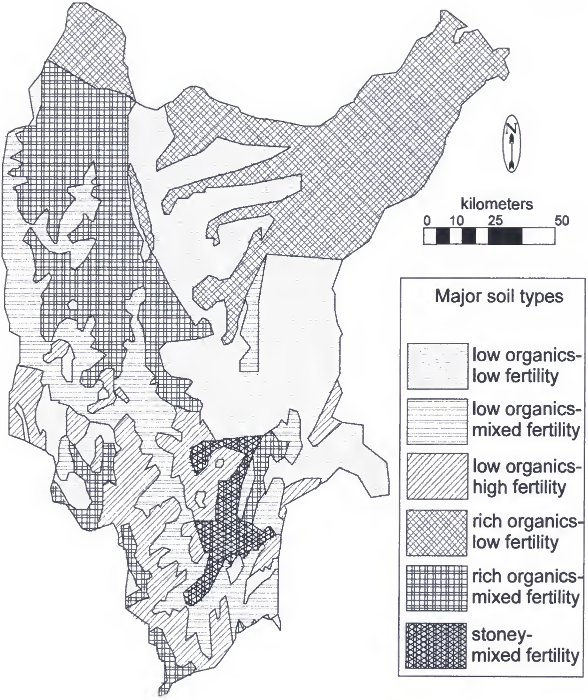


Figure 17. Major soil types in the Catatumbo River drainage basin.

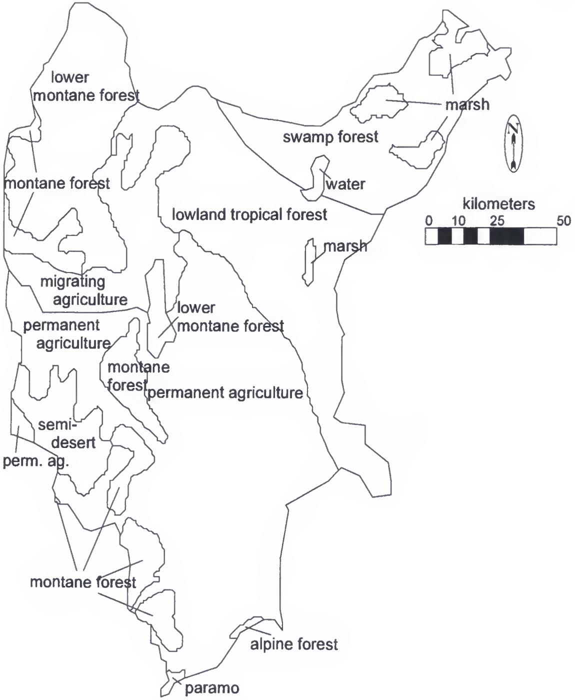


Figure 18. Dominant land cover in the Catatumbo River drainage basin.

Figure 19. Districts of the Catatumbo River drainage basin. Districts in the Venezulean sector of the basin are arbitutary divisions of the Cata. District to make the resolution of that area more similar to the Colombian side. (Cata. is an abbreviation for the Catatumbo district).

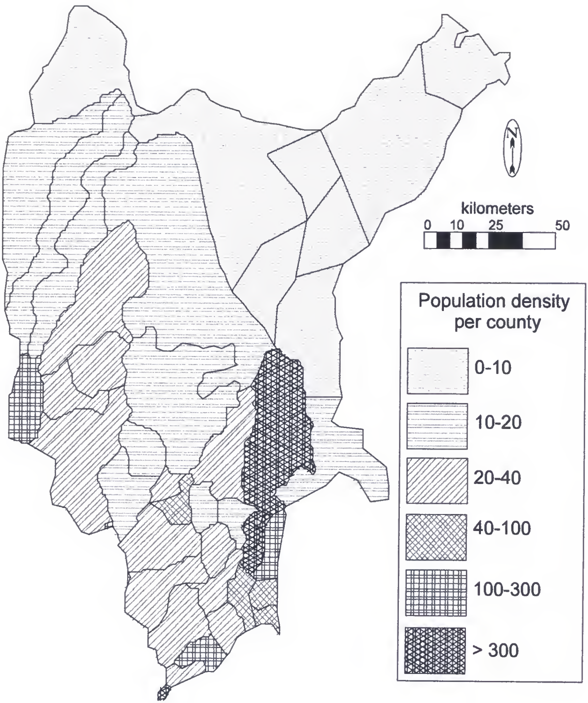


Figure 20. Distribution of population density of the Catatumbo River drainage basin.

Table 12. Agricultural production by county in the Catatumbo watershed for 1992-1993. Measurements are in tons.

County	Coffee (T)	Sugarcane (T)	Corn (T)	Rice (T)	Potato (T)	Onion (T)	Cacao (T)
Abrego	10473	8940	809	0	0	45963	0
Arboledas	0	0	256	0	0	0	0
Bochalema	0	0	106	0	0	0	0
Bucarasica	0	0	103	0	0	0	80
Cachira	0	0	5	0	0	0	0
Chinacota	0	0	94	0	0	0	0
Catatumbo	0	0	114	0	0	0	0
Convencion	0	0	956	0	0	0	0
Cucuta	0	0	683	0	0	0	0
Cucutilla	0	0	309	0	0	0	0
Durania	0	0	106	0	0	0	0
El Carmen	8652	7386	669	0	0	0	0
El Zulia	0	0	302	36865	0	0	0
Gramalote	0	0	105	0	0	0	0
Hacari	4919	4199	380	0	0	0	0
Herran	0	0	23	0	0	0	0
La Playa	2079	1775	161	0	0	9125	0
Los Patios	0	0	35	0	0	0	0
Loudres	978	835	76	0	0	0	0
Mutiscua	0	0	35	0	0	0	0
Ocaña	3398	2901	263	0	0	14912	0

Table 12. --continued.

County	Coffee (T)	Sugarcane (T)	Corn (T)	Rice (T)	Potato (T)	Onion (T)	Cacao (T)
Pamplona	0	0	58	0	4579	0	0
Pamplonita	0	0	61	0	0	0	0
Ragonvalia	0	0	56	0	0	0	0
Salazar	0	0	383	0	0	0	0
San Calixta	10502	8965	811	0	0	0	0
San Cayetano	0	0	149	18135	0	0	0
Santiago	0	0	62	0	0	0	0
Sardinata	0	0	824	0	0	0	634
Silos	0	0	7	0	5501	0	0
Teorema	0	0	649	0	0	0	0
Tibu	0	0	1114	0	0	0	1286
Villa Caro	0	0	152	0	0	0	0
Villa del Rosari	0	0	65	0	0	0	0

Table 13. Fertilizer and pesticide use by county esitmates for the Catatumbo watershed 1992-1993.

County	Nitrogen (T)	Phosphate (T)	Pesticides (T)
Abrego	8E+04	5E+04	647
Arboledas	3E+04	1E+04	204
Bochalema	1E+04	6E+03	85
Bucarasica	1E+04	6E+03	83
Cachira	5E+02	3E+02	3
Catatumbo	1E+04	7E+03	91
Chinacota	1E+04	5E+03	75
Convencion	1E+05	6E+04	764
Cucuta	7E+04	4E+04	546
Cucutilla	3E+04	2E+04	247
Durania	1E+04	6E+03	85
El Carmen	7E+04	4E+04	534
El Zulia	3E+04	2E+04	242
Gramalote	1E+04	6E+03	84
Hacari	4E+04	2E+04	304
Herran	2E+03	1E+03	19
La Playa	2E+04	9E+03	128
Los Patios	4E+03	2E+03	28
Loudres	8E+03	4E+03	60
Mutiscua	4E+03	2E+03	28
Ocaña	3E+04	2E+04	210
Pamplona	6E+03	3E+03	46
Pamplonita	6E+03	3E+03	48
Ragonvalia	6E+03	3E+03	44
Salazar	4E+04	2E+04	306
San Calixta	8E+04	5E+04	648
San Cayetano	2E+04	9E+03	119
Santiago	6E+03	4E+03	49
Sardinata	8E+04	5E+04	658
Silos	7E+02	4E+02	6
Teorema	7E+04	4E+04	519
Tibu	1E+05	6E+04	890
Villa Caro	2E+04	9E+03	122
Villa del Rosari	7E+03	4E+03	52

Table 14. Mineral production by county in the Catatumbo watershed for 1992-1993. Measurements are in tons except for oil which is in barrels.

County	Coal (T)	Oil (bbls)	Clay (T)	Limestone (T)	Phosphates (T)
Abrego	0	0	0	0	0
Arboledas	0	0	0	0	0
Bochalema	0	8E+04	0	0	0
Bucarasica	0	2E+05	2E+05	0	0
Cachira	0	1E+04	0	0	0
Chinacota	0	1E+05	0	0	0
Catatumbo	0	0	0	0	0
Convencion	0	0	0	0	0
Cucuta	0	0	0	0	0
Cucutilla	2E+04	0	0	0	0
Durania	0	0	0	0	0
El Carmen	0	0	0	0	0
El Zulia	0	0	0	0	0
Gramalote	0	0	0	0	0
Hacari	3E+05	2E+05	0	0	9E+03
Herran	4E+04	0	0	0	0
La Playa	0	0	0	0	0
Los Patios	0	8E+03	0	0	0
Loudres	0	0	0	0	0
Mutiscua	3E+04	0	0	0	0
Ocaña	3E+05	5E+05	3E+05	1.E+05	0
Pamplona	1E+04	0	0	0	0
Pamplonita	0	6E+04	0	0	0
Ragonvalia	0	0	0	0	0
Salazar	0	0	0	0	0
San Calixta	0	0	0	0	0
San Cayetano	0	0	0	0	0
Santiago	0	0	0	0	0
Sardinata	0	5E+05	0	0	0
Silos	0	0	0	0	0
Teorema	0	1E+06	0	0	0
Tibu	0	0	0	0	0
Villa Caro	0	0	0	0	0
Villa del Rosari	0	0	0	0	0

The population density of the basin's countys (Figure 20) is concentrated in Cucuta and the surrounding countys bordering Venezuela. Relatively few roads exist in the drainage basin, and the larger of those are also centered near Cucuta.

In Figure 21, the road system of the Catatumbo drainage basin is shown. Also provided are averages of car volume per day on each road. The roads are concentrated around Cucuta and extend up to populations in Venezuela where trade takes place. Road traffic is also high in the southwestern areas of the watershed where the roads connect to other parts of Colombia.

The locations of the monitoring stations used by Intevep and Ecopetrol are shown in Figure 22. The raw data used from these stations (including total nitrogen, total phosphorus, sediment load, and conductivity) are provided in Table 15.

Determination of Watersheds

The outline of the segment watersheds defined for this study are shown in Figure 23. The general attributes of each segment watershed, including the stream-order of the segment, are provided in Table 16. Figure 24 shows the outline of the stream-order watersheds delineated in the Catatumbo drainage basin. The drainage basin has up to stream-order 5.

Water Budget of Watershed

The water contributions to each segment watershed is provided in Table 17. Stream outflow can be determined by adding the runoff to the segment watershed of interest to its stream inflow.

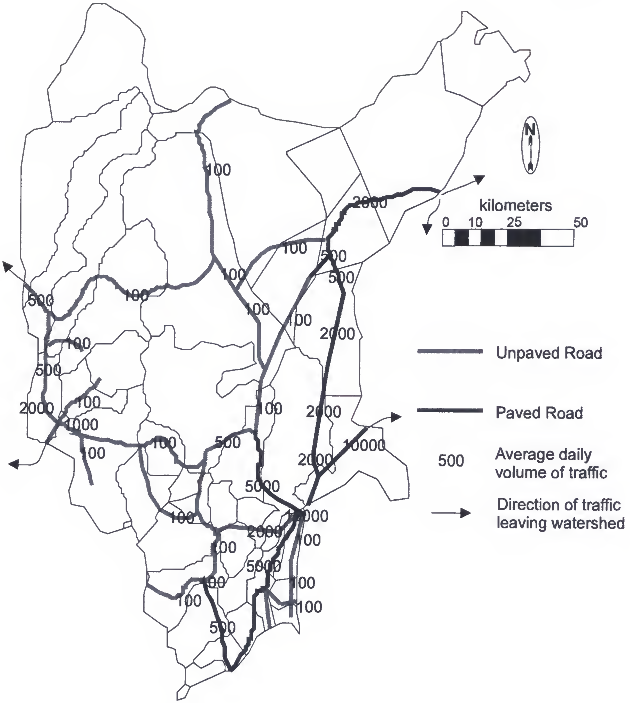


Figure 21. The road network of the Catatumbo River drainage basin. Outlines of districts are shown to aid orientation of road locations.

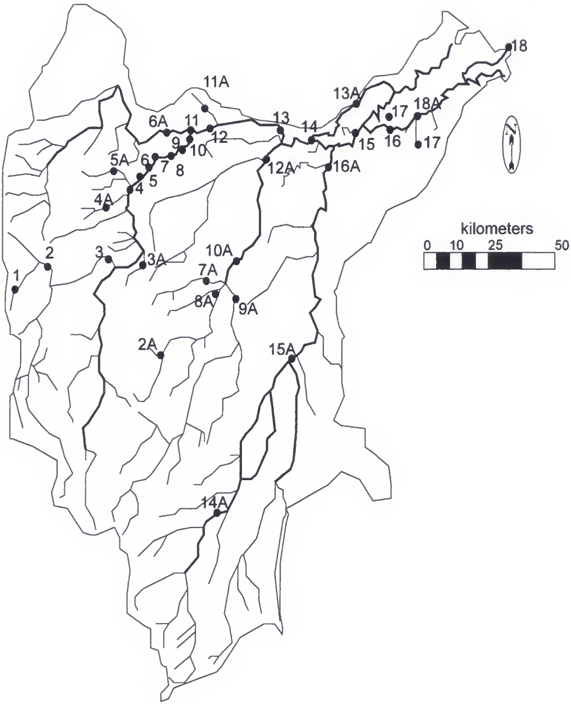


Figure 22. Locations of monitoring stations used by Ecopetrol and Intevep (1996).

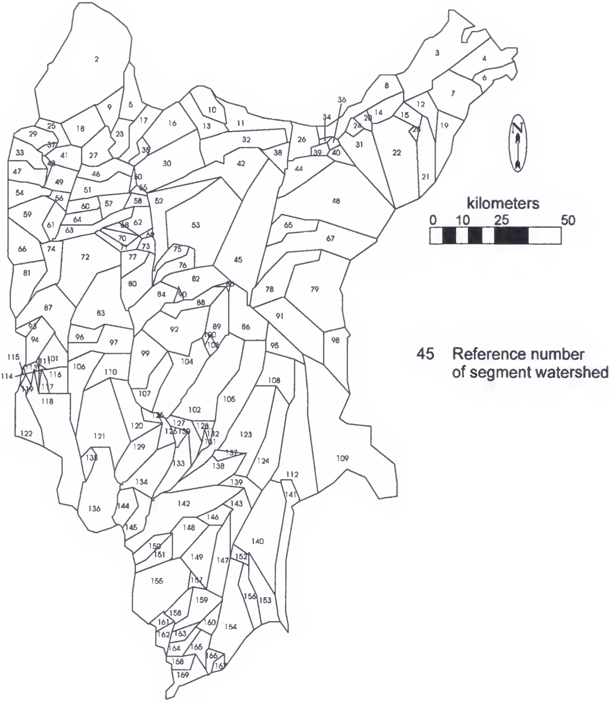


Figure 23. Organization of segment watersheds.

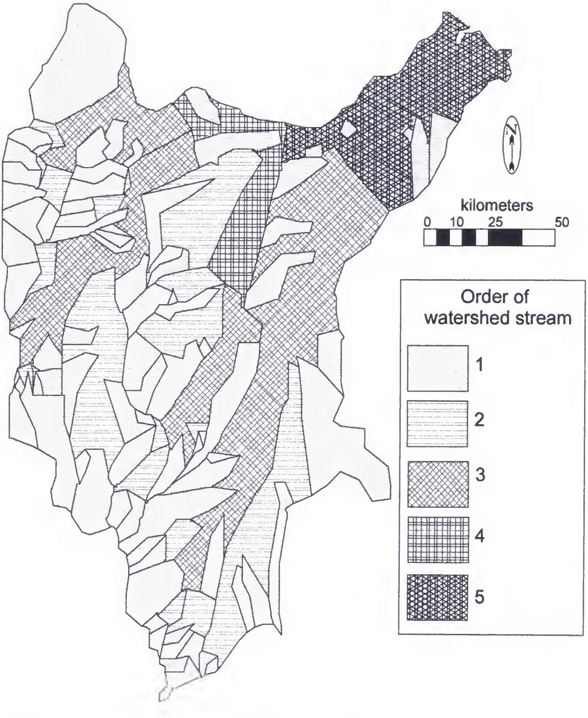


Figure 24. Organization of stream order watersheds.

Table 15. Water quality raw data for watersheds of the Catatumbo drainagebasin.

Station	Total Nitrogen mg/l	Total Phosphorus mg/l	Sediment Load MT/day	Conductivity uS/cm
1	2.28	0.46	5	
2	1.89	0.25	10	
3	1.87	0.32	15	
4	1.92	0.24	18	
5	1.57	0.57	20	
6	1.62	0.78	25	70.6
7	2.29	0.25	30	53
8	1.51	0.20	35	54
9	1.51	0.21	40	48
10	2.45	0.29	45	45
11	2.23	0.11	109	86.81
12	2.08	0.09	150	63
13	1.96	0.16	200	63
14	1.71	0.15	250	
15	1.30	0.23	300	100
16	0.00	0.20	375	119
17	1.96	0.74	400	82
18	2.11	0.24	450	80
19	1.57	0.06		
20	1.87	0.24		
1A	0.00	0.06	11	
2A	1.63	0.27	8	
3A	2.43	0.14	12	
4A	1.71	0.06	10	
5A	1.08	0.04	10	
6A	1.51	0.09	50	
7A	1.83	0.05	23	
8A	1.94	0.09	45	
9A	1.87	0.17	63	
10A	2.28	0.14	133	
11A	2.01	0.20	20	
12A	1.91	0.11	241	
13A	2.44	0.26	100	
14A	0.98	0.52	51	
15A	1.62	0.43	83	
16A	2.08	0.12	120	179
18A	2.06	0.10	200	

Table 16. List of segement and stream order watershed reference information.

Segement Watershed Ref. #	Stream Order Watershed Ref. # *	Stream Order	Main Tributary	Area km^2	Average Elevation m
1	--	--	entire basin	25606.56	
2	2	1	Oro	1025.60	300
3	3	5	Catatumbo	446.43	25
4	3	5	Catatumbo	190.50	20
5	4	3	Oro	127.17	100
6	3	5	Catatumbo	84.44	10
7	3	5	Catatumbo	233.95	25
8	3	5	Catatumbo	202.57	25
9	4	3	Oro	96.66	300
10	5	1	Catatumbo	101.49	200
11	6	4	Catatumbo	168.97	150
12	3	5	Catatumbo	91.49	25
13	6	4	Catatumbo	124.04	200
14	3	5	Catatumbo	93.78	25
15	3	5	Catatumbo	51.44	25
16	4	3	Oro	205.33	200
17	4	3	Oro	120.61	200
18	4	3	Oro	161.09	300
19	7	1	Catatumbo	150.89	25
20	3	5	Catatumbo	30.38	25
21	8	1	Catatumbo	158.86	25
22	3	5	Catatumbo	408.64	25
23	9	1	Oro	80.87	300
24	10	1	Catatumbo	23.85	25
25	11	2	Oro	56.94	1000
26	3	5	Catatumbo	123.30	100
27	12	1	Oro	123.11	300
28	13	1	Catatumbo	14.02	25
29	14	1	Oro	88.29	1000
30	15	3	Catatumbo	343.59	100
31	3	5	Catatumbo	231.31	25
32	16	1	Tarra	238.71	25
33	17	1	Oro	95.17	1000
34	3	5	Catatumbo	8.88	25
35	18	1	Oro	37.01	100
36	3	5	Catatumbo	13.13	25
37	19	1	Oro	17.53	300
38	20	4	Tarra	67.38	200

Table 16. --continued.

Segement Watershed Ref. #	Stream Order Watershed Ref. # *	Stream Order	Main Tributary	Area km^2	Average Elevation m
39	21	1	Catatumbo	24.82	150
40	22	3	Zulia	42.94	150
41	4	3	Oro	98.61	300
42	23	2	Tarra	320.22	200
43	24	2	Oro	16.84	300
44	25	1	Zulia	163.65	200
45	20	4	Tarra	636.78	200
46	26	1	Catatumbo	108.24	300
47	27	1	Oro	99.80	500
48	22	3	Zulia	737.00	100
49	28	2	Oro	100.98	300
50	29	2	Catatumbo	18.46	100
51	30	1	Catatumbo	152.30	500
52	31	1	Tarra	253.68	150
53	23	2	Tarra	547.16	200
54	32	1	Oro	103.47	500
55	15	3	Catatumbo	12.90	200
56	28	2	Oro	40.92	300
57	33	2	Catatumbo	74.47	500
58	15	3	Tarra	34.25	200
59	34	1	Oro	163.33	500
60	35	1	Catatumbo	55.67	500
61	36	1	Oro	70.98	500
62	15	3	Catatumbo	84.15	300
63	37	1	Catatumbo	121.28	500
64	38	1	Catatumbo	68.25	500
65	39	1	Zulia	117.11	200
66	40	1	Oro	155.97	500
67	22	3	Zulia	357.52	200
68	41	1	Catatumbo	22.70	300
69	15	3	Catatumbo	11.42	100
70	42	1	Catatumbo	41.47	250
71	43	1	Catatumbo	48.40	500
72	15	3	Tarra	399.92	500
73	15	3	Catatumbo	28.24	100
74	44	2	Oro	121.80	500
75	45	1	Catatumbo	52.68	100
76	46	1	Catatumbo	84.08	100

Table 16. --continued.

Segement Watershed Ref. #	Stream Order Watershed Ref. # *	Stream Order	Main Tributary	Area km^2	Average Elevation m
77	15	3	Catatumbo	68.64	300
78	47	1	Zulia	236.40	100
79	22	3	Zulia	491.13	100
80	48	1	Catatumbo	154.07	500
81	49	1	Catatumbo	179.61	500
82	50	2	Tarra	178.16	100
83	51	2	Catatumbo	335.97	500
84	52	1	Tarra	174.19	500
85	53	2	Tarra	8.03	100
86	54	3	Tarra	212.50	100
87	15	3	Oro	267.59	500
88	55	1	Tarra	105.01	300
89	53	2	Tarra	133.48	100
90	56	1	Tarra	10.78	100
91	22	3	Zulia	290.22	100
92	53	2	Tarra	276.07	300
93	57	1	Catatumbo	20.84	750
94	15	3	Catatumbo	110.62	500
95	22	3	Zulia	102.06	100
96	58	1	Tarra	72.72	500
97	51	2	Catatumbo	175.18	500
98	59	1	Zulia	158.92	200
99	60	1	Tarra	197.57	500
100	53	2	Tarra	7.99	300
101	61	1	Catatumbo	93.51	750
102	54	3	Tarra	409.61	500
103	62	1	Tarra	19.48	200
104	63	1	Tarra	273.56	500
105	64	1	Tarra	401.28	500
106	65	1	Catatumbo	198.21	750
107	66	1	Tarra	140.08	500
108	22	3	Zulia	172.35	150
109	67	1	Zulia	904.99	100
110	51	2	Catatumbo	133.92	500
111	68	2	Catatumbo	2.70	750
112	69	2	Zulia	454.47	100
113	70	2	Catatumbo	31.52	750
114	68	2	Catatumbo	11.04	750

Table 16. --continued.

Segement Watershed Ref. #	Stream Order Watershed Ref. # *	Stream Order	Main Tributary	Area km^2	Average Elevation m
115	71	1	Catatumbo	6.79	1000
116	72	1	Catatumbo	74.19	750
117	73	1	Catatumbo	22.46	750
118	74	1	Catatumbo	486.58	1500
119	75	1	Catatumbo	11.79	1000
120	76	1	Catatumbo	168.97	1000
121	51	2	Catatumbo	409.59	1000
122	77	1	Catatumbo	140.98	1500
123	22	3	Zulia	326.70	500
124	22	3	Zulia	255.16	200
125	78	1	Tarra	27.19	500
126	79	2	Tarra	48.46	500
127	54	3	Tarra	78.27	500
128	80	2	Tarra	32.59	300
129	81	1	Tarra	173.00	1000
130	54	3	Tarra	23.51	500
131	82	1	Tarra	16.01	500
132	83	1	Tarra	8.83	500
133	84	1	Tarra	124.59	1000
134	85	2	Tarra	198.17	1000
135	86	1	Catatumbo	39.12	1000
136	87	1	Catatumbo	350.78	2000
137	88	1	Zulia	26.60	500
138	89	1	Zulia	185.70	1000
139	22	3	Zulia	76.41	300
140	69	2	Zulia	404.10	1000
141	90	1	Zulia	210.42	2000
142	91	1	Catatumbo	405.56	2000
143	22	3	Zulia	113.45	500
144	92	1	Tarra	91.08	2000
145	93	1	Tarra	103.30	2000
146	22	3	Zulia	58.47	300
147	94	1	Zulia	163.59	1000
148	95	2	Zulia	125.86	1000
149	22	3	Zulia	173.51	500
150	96	1	Zulia	62.84	2000
151	97	1	Zulia	75.04	2000
152	69	2	Zulia	29.65	500

Table 16. --continued.

Segement Watershed Ref. #	Stream Order Watershed Ref. # *	Stream Order	Main Tributary	Area km^2	Average Elevation m
153	98	1	Zulia	139.82	1250
154	69	2	Zulia	318.04	1250
155	99	1	Zulia	361.12	2000
156	100	1	Zulia	101.98	1250
157	22	3	Zulia	21.56	500
158	101	2	Zulia	65.85	1000
159	102	2	Zulia	137.94	1000
160	102	2	Zulia	54.37	1000
161	103	1	Zulia	33.07	2500
162	104	1	Zulia	47.21	2500
163	105	2	Zulia	34.79	2000
164	106	1	Zulia	52.44	2000
165	107	1	Zulia	71.51	2000
166	108	1	Zulia	32.77	2500
167	109	1	Zulia	20.00	2500
168	110	1	Zulia	44.33	2500
169	111	1	Zulia	96.08	2500

* Stream order watersheds can contain more than one segment watershed.

Table 17. Water contributions to segment watersheds.

Segement Watershed Ref. #	Stream Order Watershed Ref. #	Rainfall m/yr	ET m/yr	Runoff m/yr	Stream Inflow* m3/yr
2	2	1.62	0.0240	1.29	0.00E+00
3	3	1.26	0.0360	0.91	8.74E+10
4	3	1.44	0.0360	1.08	2.20E+10
5	4	1.90	0.0480	1.56	1.35E+09
6	3	1.50	0.0360	1.14	9.76E+09
7	3	1.29	0.0360	0.93	2.68E+10
8	3	1.31	0.0360	0.96	1.69E+10
9	4	1.75	0.0480	1.42	8.75E+08
10	5	3.58	0.0600	3.24	0.00E+00
11	6	2.40	0.0720	2.04	8.30E+09
12	3	1.25	0.0360	0.89	1.04E+10
13	6	3.00	0.0720	2.64	5.84E+09
14	3	1.25	0.0360	0.89	1.05E+10
15	3	1.25	0.0360	0.89	5.79E+09
16	4	2.70	0.0480	2.35	3.06E+09
17	4	2.26	0.0480	1.92	1.51E+09
18	4	1.39	0.0480	1.06	1.23E+09
19	7	1.25	0.0840	0.89	0.00E+00
20	3	1.25	0.0360	0.89	3.37E+09
21	8	1.25	0.0960	0.89	0.00E+00
22	3	1.25	0.0360	0.89	4.57E+10
23	9	1.90	0.1080	1.57	0.00E+00
24	10	1.25	0.1200	0.89	0.00E+00
25	11	1.25	0.1320	1.01	5.73E+07
26	3	1.98	0.0360	1.62	1.01E+10
27	12	1.64	0.1440	1.31	0.00E+00
28	13	1.25	0.1560	0.89	0.00E+00
29	14	1.25	0.1680	1.01	0.00E+00
30	15	2.69	0.1800	2.33	1.02E+10
31	3	1.26	0.0360	0.90	2.54E+10
32	16	2.67	0.1920	2.31	0.00E+00
33	17	1.26	0.2040	1.01	0.00E+00
34	3	1.50	0.0360	1.14	7.41E+08
35	18	2.25	0.2160	1.89	0.00E+00
36	3	1.50	0.0360	1.14	1.11E+09
37	19	1.25	0.2280	0.92	0.00E+00
38	20	2.25	0.2400	1.90	2.12E+09

Table 17. --continued.

Segement Watershed Ref. #	Stream Order Watershed Ref. # *	Rainfall m/yr	ET m/yr	Runoff m/yr	Stream Inflow* m3/yr
39	21	1.50	0.2520	1.14	0.00E+00
40	22	1.49	0.2640	1.13	1.05E+09
41	4	1.25	0.0480	0.92	5.49E+08
42	23	2.83	0.2760	2.49	1.58E+09
43	24	1.25	0.2880	0.92	1.55E+07
44	25	2.02	0.3000	1.67	0.00E+00
45	20	2.82	0.2400	2.48	1.57E+10
46	26	1.76	0.3120	1.43	0.00E+00
47	27	1.29	0.3240	0.96	0.00E+00
48	22	1.74	0.2640	1.38	1.72E+10
49	28	1.25	0.3360	0.92	3.76E+08
50	29	2.25	0.3480	1.89	3.49E+07
51	30	1.67	0.3600	1.34	0.00E+00
52	31	2.46	0.3720	2.10	0.00E+00
53	23	2.79	0.2760	2.45	1.34E+09
54	32	1.36	0.3840	1.03	0.00E+00
55	15	2.25	0.1800	1.90	3.27E+08
56	28	1.25	0.3360	0.92	1.15E+08
57	33	1.79	0.3960	1.46	1.09E+08
58	15	2.23	0.1800	1.88	7.53E+08
59	34	1.31	0.4080	0.98	0.00E+00
60	35	1.53	0.4200	1.20	0.00E+00
61	36	1.25	0.4320	0.92	0.00E+00
62	15	2.16	0.1800	1.83	1.69E+09
63	37	1.61	0.4440	1.28	0.00E+00
64	38	1.56	0.4560	1.23	0.00E+00
65	39	2.58	0.4680	2.23	0.00E+00
66	40	1.58	0.4800	1.25	0.00E+00
67	22	2.44	0.2640	2.09	7.86E+09
68	41	1.78	0.4920	1.44	0.00E+00
69	15	2.25	0.1800	1.89	2.09E+08
70	42	1.77	0.5040	1.43	0.00E+00
71	43	1.81	0.5160	1.48	0.00E+00
72	15	1.57	0.1800	1.24	3.67E+09
73	15	2.25	0.1800	1.89	4.62E+08
74	44	1.31	0.5280	0.98	1.19E+08
75	45	2.44	0.5400	2.08	0.00E+00

Table 17. --continued.

Segement Watershed Ref. #	Stream Order Watershed Ref. # *	Rainfall m/yr	ET m/yr	Runoff m/yr	Stream Inflow* m3/yr
76	46	2.45	0.5520	2.09	0.00E+00
77	15	1.83	0.1800	1.50	9.94E+08
78	47	2.86	0.5640	2.50	0.00E+00
79	22	2.81	0.2640	2.46	9.77E+09
80	48	1.82	0.5760	1.49	0.00E+00
81	49	1.68	0.5880	1.35	0.00E+00
82	50	2.52	0.6000	2.16	3.85E+08
83	51	1.60	0.6120	1.27	1.27E+09
84	52	1.77	0.6240	1.44	0.00E+00
85	53	2.75	0.6360	2.39	5.78E+07
86	54	2.45	0.6480	2.09	2.73E+09
87	15	1.58	0.1800	1.25	1.86E+09
88	55	2.15	0.6600	1.82	0.00E+00
89	53	2.28	0.6360	1.92	6.41E+08
90	56	2.11	0.6720	1.75	0.00E+00
91	22	2.42	0.2640	2.06	5.06E+09
92	53	1.80	0.6360	1.47	4.05E+08
93	57	1.75	0.6840	1.43	0.00E+00
94	15	1.75	0.1800	1.42	6.32E+08
95	22	1.96	0.2640	1.61	1.57E+09
96	58	1.30	0.6960	0.97	0.00E+00
97	51	1.29	0.6120	0.96	4.42E+08
98	59	9.75	0.7080	9.40	0.00E+00
99	60	1.45	0.7200	1.12	0.00E+00
100	53	1.75	0.6360	1.42	2.31E+07
101	61	1.72	0.7320	1.40	0.00E+00
102	54	1.77	0.6480	1.44	4.40E+09
103	62	1.75	0.7440	1.40	0.00E+00
104	63	1.72	0.7560	1.38	0.00E+00
105	64	1.77	0.7680	1.44	0.00E+00
106	65	0.85	0.7800	0.53	0.00E+00
107	66	1.46	0.7920	1.13	0.00E+00
108	22	1.75	0.2640	1.39	1.67E+09
109	67	1.29	0.8040	0.93	0.00E+00
110	51	1.25	0.6120	0.92	2.09E+08
111	68	1.75	0.8160	1.43	3.87E+06
112	69	1.19	0.8280	0.83	1.84E+09

Table 17. --continued.

Segement Watershed Ref. #	Stream Order Watershed Ref. # *	Rainfall m/yr	ET m/yr	Runoff m/yr	Stream Inflow* m3/yr
113	70	1.75	0.8400	1.43	9.03E+07
114	68	1.75	0.8160	1.43	1.58E+07
115	71	1.75	0.8520	1.51	0.00E+00
116	72	0.91	0.8640	0.59	0.00E+00
117	73	1.52	0.8760	1.20	0.00E+00
118	74	1.25	0.8880	1.07	0.00E+00
119	75	1.75	0.9000	1.51	0.00E+00
120	76	1.25	0.9120	1.01	0.00E+00
121	51	0.89	0.6120	0.65	2.65E+08
122	77	1.75	0.9240	1.57	0.00E+00
123	22	1.74	0.2640	1.41	1.43E+09
124	22	1.30	0.2640	0.96	1.00E+09
125	78	1.25	0.9360	0.92	0.00E+00
126	79	1.54	0.9480	1.21	5.87E+07
127	54	1.75	0.6480	1.43	6.17E+08
128	80	1.75	0.9600	1.42	4.62E+07
129	81	1.25	0.9720	1.01	0.00E+00
130	54	1.75	0.6480	1.43	1.52E+08
131	82	1.75	0.9840	1.43	0.00E+00
132	83	1.75	0.9960	1.43	0.00E+00
133	84	1.64	1.0080	1.40	0.00E+00
134	85	1.33	1.0200	1.08	2.14E+08
135	86	1.24	1.0320	1.00	0.00E+00
136	87	1.32	1.0440	1.14	0.00E+00
137	88	1.75	1.0560	1.43	0.00E+00
138	89	1.60	1.0680	1.35	0.00E+00
139	22	1.45	0.2640	1.12	2.27E+08
140	69	1.30	0.8280	1.05	1.30E+09
141	90	1.20	1.0800	1.02	0.00E+00
142	91	1.31	1.0920	1.13	0.00E+00
143	22	1.49	0.2640	1.17	2.11E+08
144	92	1.25	1.1040	1.07	0.00E+00
145	93	1.25	1.1160	1.07	0.00E+00
146	22	1.02	0.2640	0.69	4.45E+08
147	94	1.75	1.1280	1.51	0.00E+00
148	95	1.40	1.1400	1.16	1.45E+08
149	22	1.56	0.2640	1.24	1.00E+09

Table 17. --continued.

Segement Watershed Ref. #	Stream Order Watershed Ref. # *	Rainfall m/yr	ET m/yr	Runoff m/yr	Stream Inflow* m3/yr
150	96	1.25	1.1520	1.07	0.00E+00
151	97	1.25	1.1640	1.07	0.00E+00
152	69	1.75	0.8280	1.43	6.42E+07
153	98	1.56	1.1760	1.31	0.00E+00
154	69	0.98	0.8280	0.73	2.33E+08
155	99	1.25	1.1880	1.07	0.00E+00
156	100	1.54	1.2000	1.29	0.00E+00
157	22	1.67	0.2640	1.35	9.78E+07
158	101	1.25	1.2120	1.01	7.69E+07
159	102	1.41	1.2240	1.17	2.78E+08
160	102	1.25	1.2240	1.01	5.49E+07
161	103	1.25	1.2360	1.11	0.00E+00
162	104	1.25	1.2480	1.11	0.00E+00
163	105	1.25	1.2600	1.11	0.00E+00
164	106	1.25	1.2720	1.11	0.00E+00
165	107	1.12	1.2840	0.98	0.00E+00
166	108	0.55	1.2960	0.41	0.00E+00
167	109	0.50	1.3080	0.36	0.00E+00
168	110	0.55	1.3200	0.41	0.00E+00
169	111	0.83	1.3320	0.69	0.00E+00

*First order stream did not have stream inflow.

Empower Density

The results of the spatial analysis of empower density are divided into the results for renewable empower density and development empower density. In general, renewable empower density increases downstream and with the order of the stream-order watershed. Development empower density is concentrated in the upper watersheds and decreases with the order of the stream-order watersheds.

Renewable empower density

Available geo-potential empower density increases in a longitudinal direction towards the mouth of the Catatumbo River (Figure 25). The main channel of the Catatumbo River had the largest geo-potential empower density which increases further when all the streams combined to form the fifth-order watershed. As shown in the map, geo-potential empower density ranges from 1E10 sej/m^2/yr to over 5E13 sej/m^2/yr.

In Figure 26, the spatial distribution of available chemical potential empower density is shown. In general, chemical potential empower density also increases in a downstream longitudinal pattern with the exception of a few watersheds that has higher salinity such as in the northwestern areas of the drainage basin. The range of chemical potential empower density is less than that of geo-potential empower density, and stays between 1E11 sej/m^2/yr to less than 5E13 sej/m^2/yr.

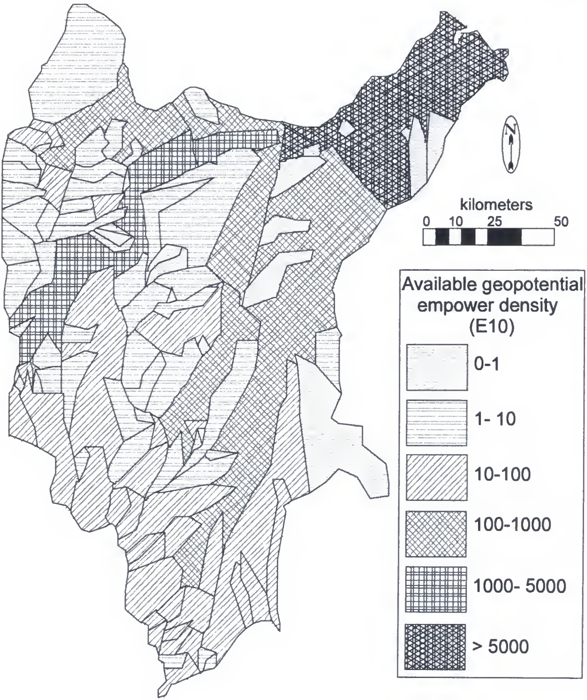


Figure 25. Available geopotential empower density in stream order watersheds of the Catatumbo River drainage basin.

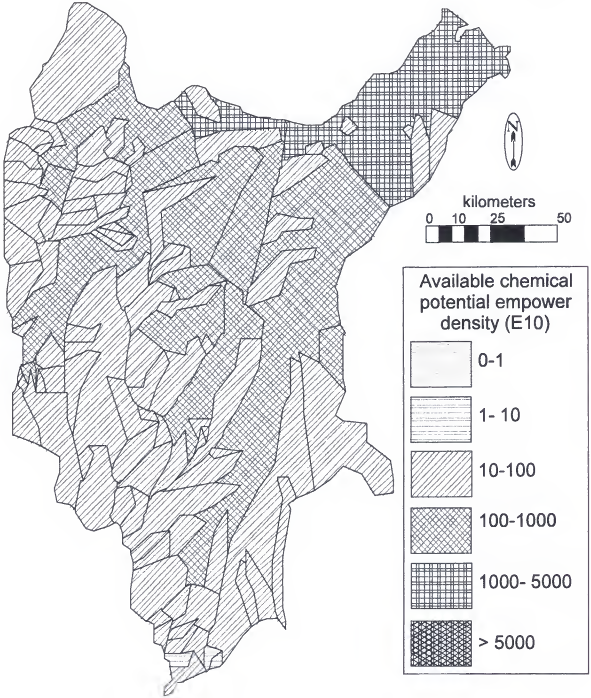


Figure 26. Available chemical potential empower density in stream order watersheds of the Catatumbo River drainage basin.

The spatial pattern of geological input empower density is shown in Figure 27. Geological inputs are largest where elevations are highest. This trend also creates a longitudinal pattern but inverse to stream direction. The range of geological input empower density is within less than 1E10 sej/m^2/yr to less than 1E13 sej/m^2/yr.

Total renewable empower density, presented in Figure 28, shows an increase in empower density as the stream join downstream. The highest renewable empower density follows the main channel of the Catatumbo and Oro Rivers. The range of renewable empower density is between 1E11 sej/m^2/yr and over 5E13 sej/m^2/yr. A summary of the renewable contributions to each stream-order watershed of the Catatumbo drainage basin is provided in Table 18.

The renewable sources of empower density are summarized by stream-order watershed in Figure 29. Average geo-potential empower density increases with stream-order watershed; however the third and fourth-order watersheds have similar empower density at 6.5E12 and 7.9E12 sej/m^2/yr. Average chemical potential empower density also increases with stream-order watersheds. Total renewable empower density increases stream-order watershed with relatively large increases between the second and third-order watersheds (1.7E12-1E13 sej/m^2/yr) and the fourth and fifth watersheds (1.7E13-7.5E13 sej/m^2/yr).

Development empower density

Fuel use empower density is shown in Figure 30. The empower density of fuel use is concentrated in the upper watersheds especially along the main

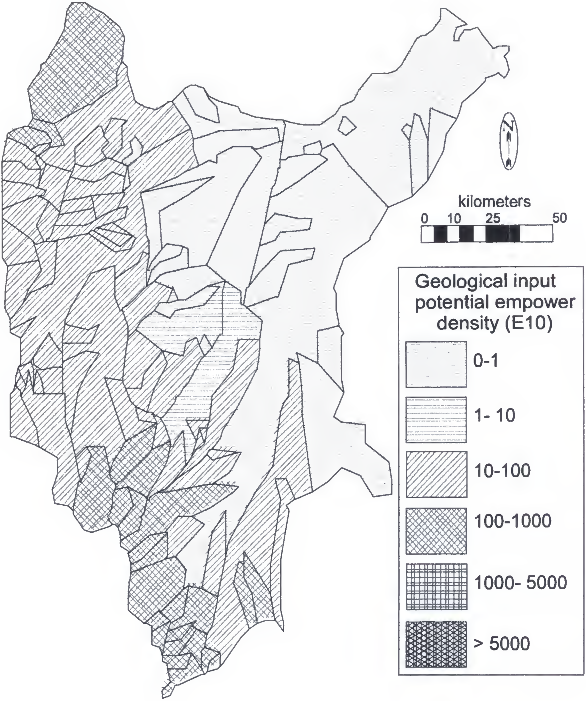


Figure 27. Geological input empower density in stream order watersheds of the Catatumbo River drainage basin.

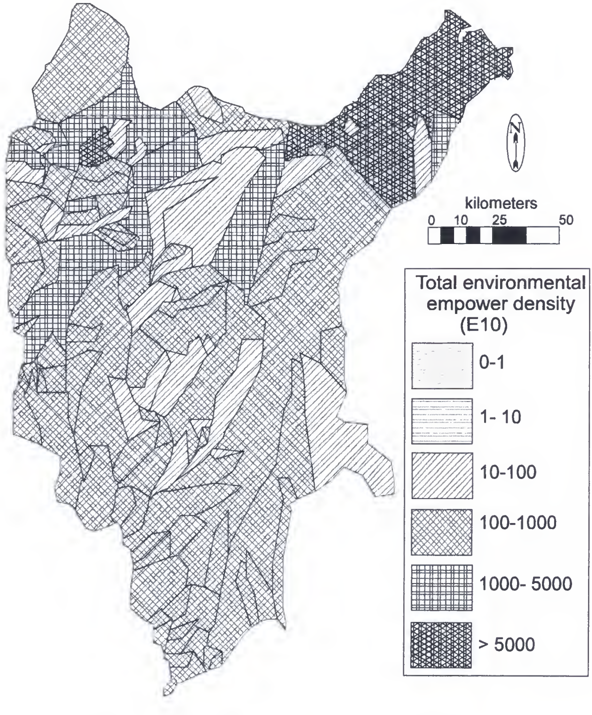


Figure 28. Total environmental empower density (geo-potential, chemical potential and geologic input) in stream order watersheds of the Catatumbo River drainage basin.

Table 18. Summary of the empower density of environmental contributions to the Catatumbo drainage basin.

Stream Order Watershed Ref. #	Available Geo-potential sej/m2/yr (E10)	Available Chemical Potential sej/m2/yr (E10)	Geologic Input sej/m2/yr (E10)	Total Renewable Contributions sej/m2/yr (E10)
2	1.76	33.89	283.21	318.86
3	4507.70	4346.31	0	8854.01
4	107.61	2884.67	17.99	3010.27
5	1.11	40.65	0	41.76
6	820.38	58.29	0	878.67
7	0.06	3751.53	0	3751.59
8	0.06	34.44	0	34.50
9	3.22	24.59	12.02	39.83
10	0.01	26.30	0	26.31
11	32.99	1380.28	103.63	1516.90
12	1.79	5141.54	18.5	5161.83
13	0.01	58.52	0	58.53
14	11.00	26.46	158.11	195.57
15	1179.79	540.62	26.39	1746.80
16	0.63	43.19	0	43.82
17	6.92	1085.68	66.23	1158.83
18	1.29	37.24	0	38.53
19	1.88	25.94	35.46	63.28
20	762.48	1091.68	0	1854.16
21	0.78	114.91	0	115.69
22	635.05	152.41	0	787.46
23	4.52	43.05	0	47.57
24	3.76	1135.51	36.21	1175.48
25	0.69	37.57	0	38.26
26	3.91	885.63	15.92	905.46
27	6.54	37.36	48.47	92.37
28	25.59	437.21	16.17	478.97
29	1.94	804.81	0	806.75
30	3.66	88.64	24.27	116.57
31	1.43	53.01	0	54.44
32	7.03	53.34	51.64	112.01
33	11.97	723.52	15.24	750.73
34	2.67	63.14	41.02	106.83
35	3.27	1025.53	60.53	1089.33
36	2.51	38.72	23.77	65.00

Table 18. --continued.

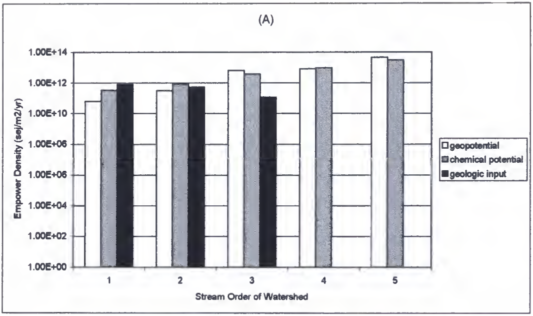
Stream Order Watershed Ref. #	Available Geo-potential sej/m2/yr (E10)	Available Chemical Potential sej/m2/yr (E10)	Geologic Input sej/m2/yr (E10)	Total Renewable Contributions sej/m2/yr (E10)
37	3.50	35.28	42.98	81.76
38	3.36	131.50	58.59	193.45
39	0.61	205.13	0	205.74
40	3.41	37.53	86.32	127.26
41	3.94	340.04	16.43	360.41
42	0.98	561.32	25.18	587.48
43	4.05	370.04	25.36	399.45
44	8.03	46.66	50.14	104.83
45	0.71	239.05	0	239.76
46	0.71	45.20	0	45.91
47	0.85	741.35	0	742.20
48	4.07	92.04	30.32	126.43
49	9.21	37.16	78.86	125.23
50	2.21	305.78	0	307.99
51	32.59	261.51	65.87	359.97
52	5.91	29.86	21.54	57.31
53	28.28	377.99	4.16	410.43
54	183.96	31.79	6.31	222.06
55	4.98	428.69	0	433.67
56	0.60	25.57	1.11	27.28
57	9.78	115.74	83.67	209.19
58	2.64	103.81	76.91	183.36
59	6.42	205.62	0	212.04
60	3.06	170.73	57.38	231.17
61	3.82	80.04	68.96	152.82
62	0.48	38.28	0	38.76
63	3.78	16.99	20.01	40.78
64	5.90	31.61	12.41	49.92
65	1.45	27.25	85.05	113.75
66	3.08	38.28	0	41.36
67	0.32	26.30	67.68	94.30
68	24.83	68.90	67.68	161.41
69	81.68	187.20	49.97	318.85
70	87.99	339.28	90.48	517.75
71	1.03	105.56	91.06	197.65
72	1.21	26.30	90.89	118.40

Table 18. --continued.

Stream Order Watershed Ref. #	Available Geo-potential sej/m2/yr (E10)	Available Chemical Potential sej/m2/yr (E10)	Geologic Input sej/m2/yr (E10)	Total Renewable Contributions sej/m2/yr (E10)
73	3.28	271.54	90.14	364.96
74	14.60	37.16	96.47	148.23
75	4.11	37.16	91.06	132.33
76	6.87	35.63	24.97	67.47
77	21.41	79.28	98.18	198.87
78	3.14	26.06	90.14	119.34
79	12.41	28.99	66.03	107.43
80	11.62	37.16	19.69	68.47
81	6.87	34.61	155.8	197.28
82	3.91	137.33	45.03	186.27
83	0.98	160.23	39.17	200.38
84	9.53	26.07	59.31	94.91
85	22.16	28.59	128.97	179.72
86	1.36	83.42	91.06	175.84
87	15.59	27.22	139.94	182.75
88	3.91	27.22	56.48	87.61
89	9.24	365.70	57	431.94
90	13.93	38.28	49.12	101.33
91	15.37	81.04	113.5	209.91
92	14.58	270.24	216.79	501.61
93	14.58	27.22	189.94	231.74
94	16.46	27.22	69.68	113.36
95	37.88	104.24	61.21	203.33
96	14.58	33.66	187.87	236.11
97	14.58	38.30	186.49	239.37
98	16.15	27.30	142.92	186.37
99	14.63	33.16	177.7	225.49
100	15.89	214.89	113.7	344.48
101	36.50	56.78	165.47	258.75
102	33.47	112.91	143.83	290.21
103	22.76	27.87	274.91	325.54
104	22.76	27.87	266.09	316.72
105	15.18	27.87	187.63	230.68
106	15.18	27.87	262.53	305.58
107	13.41	24.78	194.79	232.98
108	8.44	11.12	213.73	233.29

Table 18. --continued.

Stream Order Watershed Ref. #	Available Geo-potential sej/m2/yr (E10)	Available Chemical Potential sej/m2/yr (E10)	Geologic Input sej/m2/yr (E10)	Total Renewable Contributions sej/m2/yr (E10)
109	7.40	9.90	241.34	258.64
110	8.44	11.12	284.38	303.94
111	14.12	17.77	263.61	295.50



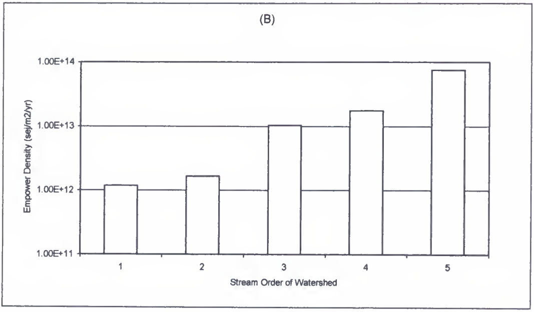


Figure 29. A) Geo-potential, chemical potential, and geological input empower density and B) total environmental empower density averaged by stream orderfor the Catatumbo drainage basin.

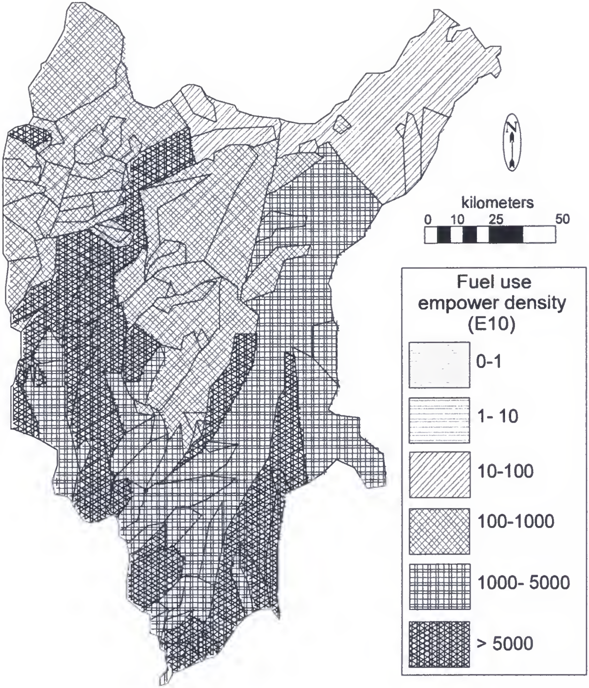


Figure 30. Fuel use empower density (adjusted by average income of district) in stream order watersheds of the Catatumbo River drainage basin.

channel of the Catatumbo River and the eastern watersheds of the Zulia River. Only the more populated areas of the Venezuelan side of the drainage basin had fuel use empower density over 1E12 sej/yr. Overall, fuel use empower density ranges from less than 1E10 sej/yr to over 5E13 sej/yr.

The empower density of goods and services is shown in Figure 31. Much of the upper drainage basin areas have empower density over 5E13 sej/yr. The lower areas of the; however, have between less than 1E10 sej/yr and 1E12 sej/yr.

The graph in Figure 32 summarizes the average empower density of fuel use and goods and services by stream-order watershed. Average fuel use empower density does not have a clear trend with stream-order density. Moreover, the range of the average empower density of fuel use is decreased to be within only one order of magnitude. The average of the empower density of goods and services does decrease with stream-order watershed with the exception of the second-order watersheds where it increases to 1E16 sej/yr.

Agricultural production as empower density, Figure 33, is concentrated along the Zulia River and the east upper tributaries of the main channel of the Catatumbo River. The majority of the drainage basin has relatively low empower density in the form of agricultural production at less than 1E10 sej/yr.

In Figure 34(A), agricultural production is averaged by stream-order watershed. Agricultural production as empower density decreases with stream-order watershed. In the lower half of the figure, (34B), the empower density of fertilizers and pesticides is averaged by stream-order watershed. Both also

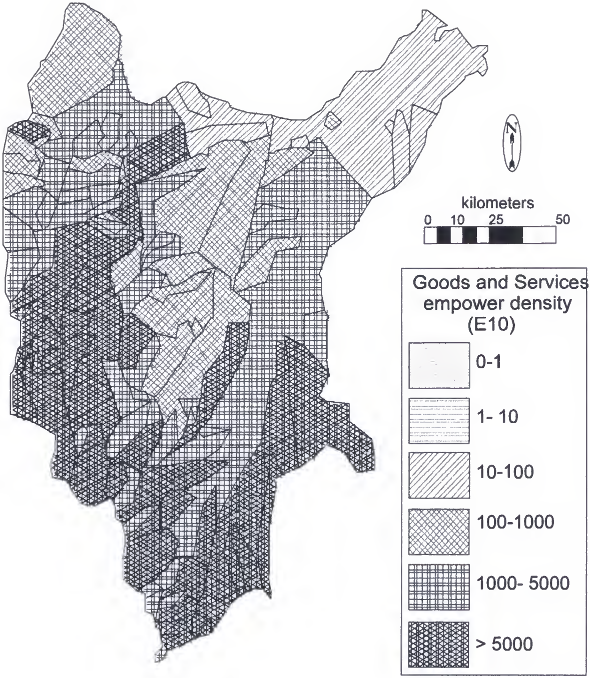


Figure 31. Goods and service contributions as empower density (adjusted by average income in district) in stream order watersheds of the Catatumbo River drainage basin.

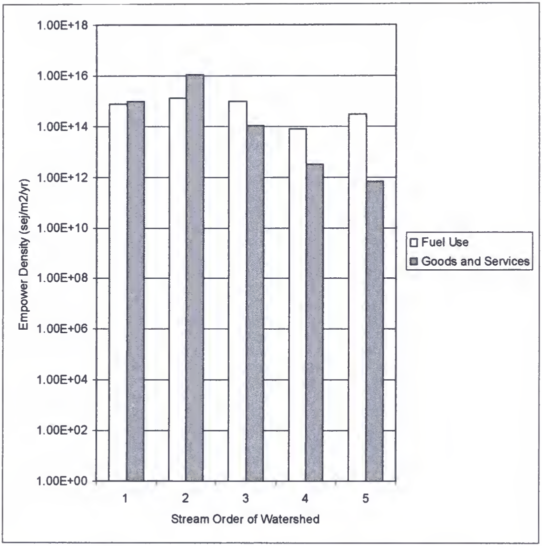


Figure 32. Fuel use and goods and services (adjusted by average income to district) contributions to stream order watersheds in the Catatumbo drainage basin.

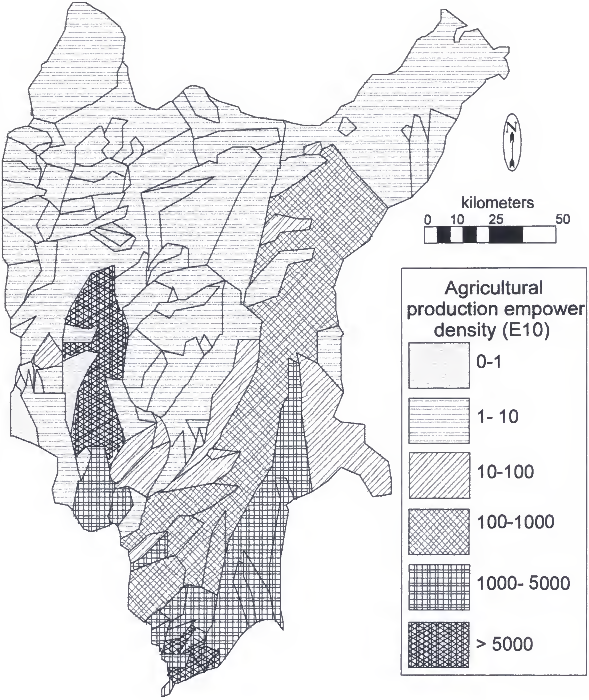


Figure 33. Agricultural production as empower density in stream order watersheds of the Catatumbo River drainage basin.

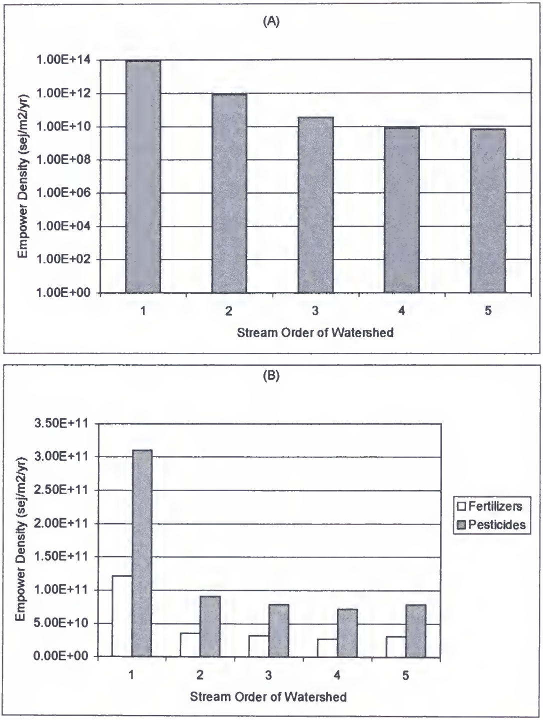


Figure 34. A) Agricultural production as empower density and B) fertilizers and pesticide contributions to stream order watersheds in the Catatumbo drainage basin.

decrease with stream-order watershed; however, fertilizer and pesticide use is much higher in the first-order watersheds than in the rest of the drainage basin.

The spatial distribution of coal and oil mining production is shown in Figure 35. Mining of these substances occurs in approximately one half of the watershed. The largest empower density is located in the eastern upper tributaries of the main channel of the Catatumbo River. The remainder mostly occurs between 1E11-1E12 sej/yr along the borders Colombian eastern and southern borders of the drainage basin.

Empower density of other mining production (clay, limestone, phosphorus rock) is concentrated in the along the main channel of the Catatumbo River until it combines with the Oro River (Figure 36). The highest empower density is in the same watersheds as that for mining of oil and coal.

A summary of mining production is shown in Figure 37. Empower density is highest in the second-order watersheds and decreases significantly in the third-order watersheds. No mining occurs in the fourth or fifth-order watersheds.

The spatial distribution of total development empower density is shown in Figure 38. Empower density is relatively lower in the lower watersheds of the Catatumbo drainage basin. In the upper watersheds, empower density of development increases, but is largest in the upper tributaries of the main channel of the Catatumbo River and along the eastern tributaries of the Zulia River. Development empower density for each stream-order watershed is given in Table 19.

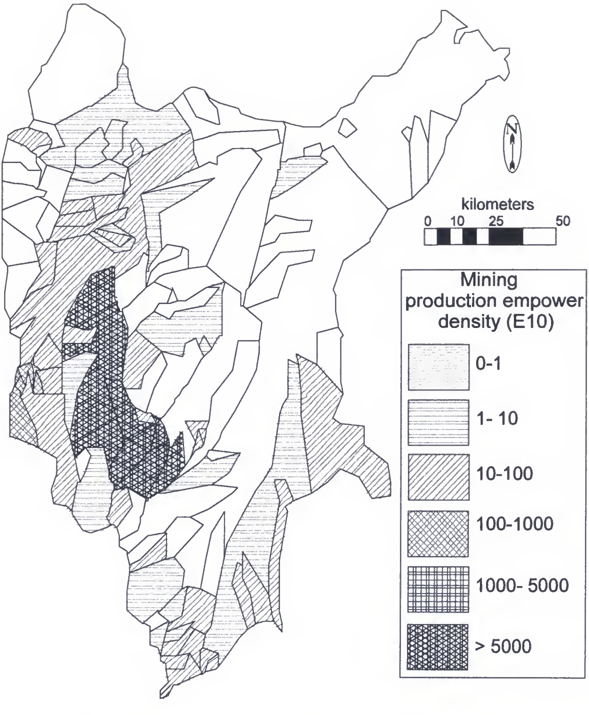


Figure 35. Mining production (coal and oil) as empower density in stream order watersheds of the Catatumbo River drainage basin.

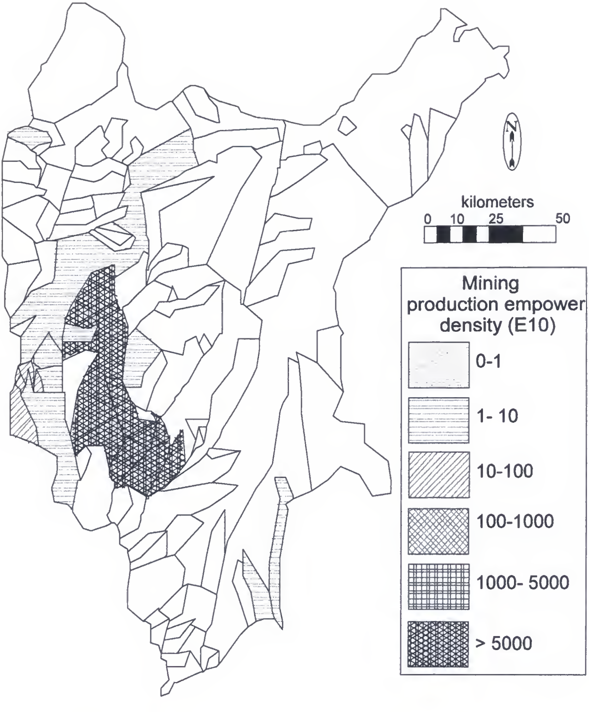


Figure 33. Mining production (clay, limestone, and phosphorus) as empower density in stream order watersheds of the Catatumbo River drainage basin.

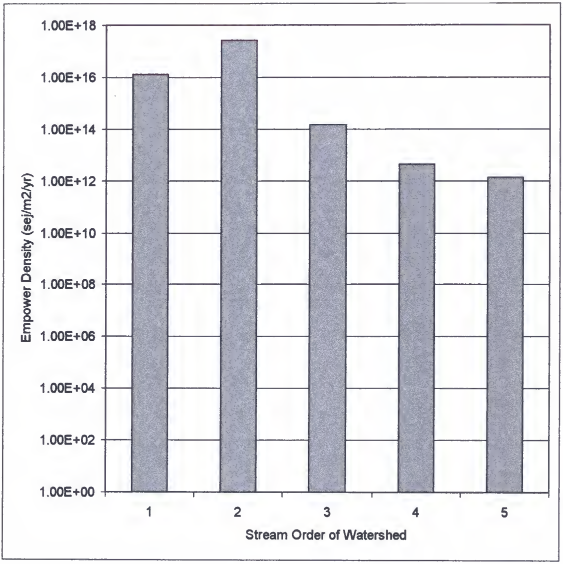


Figure 39. Total development empower density for stream order watersheds in the Catatumbo drainage basin.

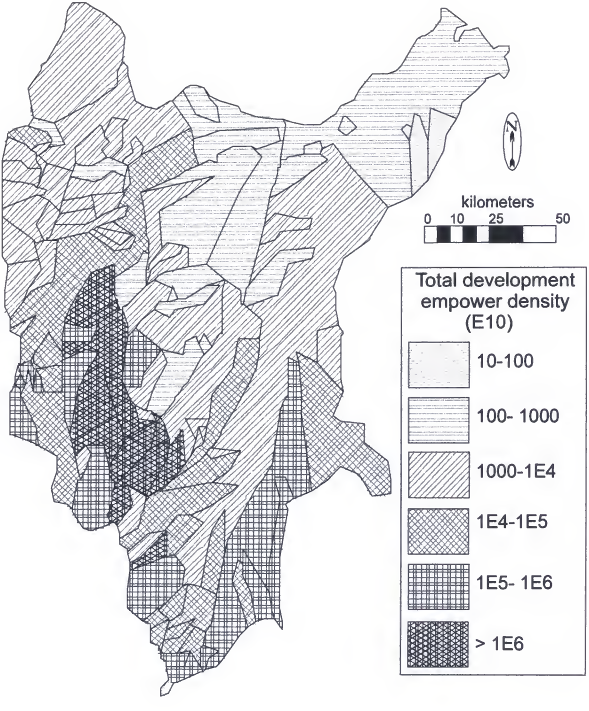


Figure 38. Total development empower in stream order watersheds of the Catatumbo River drainage basin.

Table 19. Summary of development empower density in the Catatumbo drainage basin.

Stream Order Watershed Ref. #	Fuel Use sej/m2/yr (E10)	Goods and Services sej/m2/yr (E10)	Agricultural Production sej/m2/yr (E10)	Mining Oil and Coal sej/m2/yr (E10)	Mining Other Minerals sej/m2/yr (E10)	Total Development Empower sej/m2/yr (E10)
2	2.93E+02	9.33E+02	8.94E+00	0.00E+00	0.00E+00	1.23E+03
3	5.94E+01	6.34E+01	6.37E+00	0.00E+00	0.00E+00	1.29E+02
4	3.43E+02	1.03E+03	4.59E+00	3.33E+00	0.00E+00	1.38E+03
5	9.16E+01	9.79E+01	3.73E+00	0.00E+00	0.00E+00	1.93E+02
6	9.16E+01	9.79E+01	3.73E+00	0.00E+00	0.00E+00	1.93E+02
7	2.38E+01	2.54E+01	4.12E+00	0.00E+00	0.00E+00	5.33E+01
8	2.38E+01	2.54E+01	4.12E+00	0.00E+00	0.00E+00	5.33E+01
9	5.66E+02	1.81E+03	4.11E+00	5.27E+00	0.00E+00	2.39E+03
10	1.37E+02	1.46E+02	8.35E+00	0.00E+00	0.00E+00	2.91E+02
11	1.38E+02	1.66E+02	7.40E+00	0.00E+00	0.00E+00	3.12E+02
12	3.47E+02	1.11E+03	8.08E+00	6.85E+00	0.00E+00	1.47E+03
13	2.38E+01	2.54E+01	4.12E+00	0.00E+00	0.00E+00	5.33E+01
14	1.17E+04	3.74E+04	2.92E+00	6.31E+01	6.82E+01	4.93E+04
15	1.17E+04	3.74E+04	2.92E+00	6.31E+01	6.82E+01	4.93E+04
16	9.16E+01	9.79E+01	3.73E+00	0.00E+00	0.00E+00	1.93E+02
17	2.95E+02	9.47E+02	8.96E+00	0.00E+00	0.00E+00	1.25E+03
18	4.04E+02	1.21E+03	3.23E+00	2.82E+01	0.00E+00	1.64E+03
19	2.95E+02	9.47E+02	8.96E+00	0.00E+00	0.00E+00	1.25E+03
20	1.21E+02	3.57E+02	2.41E+00	0.00E+00	0.00E+00	4.80E+02
21	6.82E+01	7.28E+01	1.18E+01	0.00E+00	0.00E+00	1.53E+02
22	2.23E+03	6.62E+03	6.31E+02	2.64E-02	0.00E+00	9.48E+03
23	1.10E+02	2.65E+02	2.50E+00	0.00E+00	0.00E+00	3.77E+02
24	2.95E+02	9.47E+02	8.96E+00	0.00E+00	0.00E+00	1.25E+03
25	2.48E+02	6.87E+02	5.10E+00	3.44E+00	0.00E+00	9.43E+02
26	2.48E+02	6.87E+02	5.10E+00	3.44E+00	0.00E+00	9.43E+02

Table 19. --continued.

Stream Order Watershed Ref. #	Fuel Use sej/m2/yr (E10)	Goods and Services sej/m2/yr (E10)	Agricultural Production sej/m2/yr (E10)	Mining Oil and Coal sej/m2/yr (E10)	Mining Other Minerals sej/m2/yr (E10)	Total Development Empower sej/m2/yr (E10)
27	2.95E+02	9.47E+02	8.96E+00	0.00E+00	0.00E+00	1.25E+03
28	3.75E+02	1.20E+03	7.52E+00	0.00E+00	0.00E+00	1.58E+03
29	1.24E+02	3.97E+02	1.53E+00	0.00E+00	0.00E+00	5.22E+02
30	5.47E+02	1.75E+03	3.48E+00	7.16E+00	0.00E+00	2.31E+03
31	1.24E+02	3.97E+02	1.53E+00	0.00E+00	0.00E+00	5.22E+02
32	2.95E+02	9.47E+02	8.96E+00	0.00E+00	0.00E+00	1.25E+03
33	4.45E+02	1.43E+03	2.32E+00	3.08E+01	0.00E+00	1.90E+03
34	5.44E+02	1.75E+03	4.46E+00	0.00E+00	0.00E+00	2.29E+03
35	5.94E+02	1.90E+03	3.70E+00	1.99E+01	0.00E+00	2.52E+03
36	3.62E+02	1.16E+03	7.77E+00	0.00E+00	0.00E+00	1.53E+03
37	5.03E+02	1.61E+03	3.41E+00	1.31E+01	0.00E+00	2.13E+03
38	6.21E+02	1.99E+03	3.30E+00	3.41E+01	0.00E+00	2.65E+03
39	2.36E+03	2.52E+03	1.32E+01	0.00E+00	0.00E+00	4.90E+03
40	5.49E+02	1.76E+03	4.37E+00	0.00E+00	0.00E+00	2.31E+03
41	3.03E+02	9.72E+02	2.19E+00	8.86E+00	0.00E+00	1.29E+03
42	6.26E+02	2.01E+03	3.72E+00	1.03E+01	0.00E+00	2.64E+03
43	6.25E+02	2.00E+03	3.73E+00	9.84E+00	0.00E+00	2.64E+03
44	3.87E+02	1.24E+03	7.38E+00	1.20E+01	0.00E+00	1.65E+03
45	5.92E+02	1.90E+03	3.82E+00	0.00E+00	0.00E+00	2.49E+03
46	6.18E+02	1.98E+03	3.95E+00	0.00E+00	0.00E+00	2.60E+03
47	4.72E+02	5.12E+02	4.02E+00	0.00E+00	0.00E+00	9.89E+02
48	1.71E+02	5.47E+02	1.76E+00	0.00E+00	0.00E+00	7.19E+02
49	3.82E+02	1.22E+03	7.40E+00	0.00E+00	0.00E+00	1.61E+03
50	1.24E+02	3.97E+02	1.53E+00	0.00E+00	0.00E+00	5.22E+02
51	2.15E+06	6.89E+06	1.32E+05	3.24E+07	1.13E+08	1.54E+08

Table 19. --continued.

Stream Order Watershed Ref. #	Fuel Use sej/m2/yr (E10)	Goods and Services sej/m2/yr (E10)	Agricultural Production sej/m2/yr (E10)	Mining Oil and Coal sej/m2/yr (E10)	Mining Other Minerals sej/m2/yr (E10)	Total Development Empower sej/m2/yr (E10)
52	6.14E+02	1.97E+03	3.93E+00	0.00E+00	0.00E+00	2.59E+03
53	3.10E+02	9.94E+02	1.15E+00	9.64E+00	0.00E+00	1.32E+03
54	7.23E+02	7.73E+02	8.00E+00	8.04E-03	0.00E+00	1.50E+03
55	1.24E+02	3.97E+02	1.53E+00	0.00E+00	0.00E+00	5.22E+02
56	1.24E+02	3.97E+02	1.53E+00	0.00E+00	0.00E+00	5.22E+02
57	5.56E+02	1.78E+03	4.26E+00	1.40E-01	0.00E+00	2.34E+03
58	7.54E+04	2.42E+05	5.21E+00	9.81E+01	2.46E+01	3.17E+05
59	1.31E+03	1.40E+03	8.91E+00	0.00E+00	0.00E+00	2.71E+03
60	7.01E+04	2.25E+05	5.10E+00	9.13E+01	2.29E+01	2.95E+05
61	7.38E+03	2.37E+04	2.05E+01	2.11E+01	2.18E+01	3.11E+04
62	1.93E+02	6.18E+02	1.39E+00	3.57E+00	0.00E+00	8.16E+02
63	1.27E+02	4.07E+02	1.53E+00	1.66E-01	0.00E+00	5.36E+02
64	1.54E+04	4.94E+04	5.71E+01	1.63E-01	0.00E+00	6.49E+04
65	3.38E+04	1.08E+05	6.62E-01	1.19E+00	2.99E-01	1.42E+05
66	1.20E+03	3.85E+03	6.88E+00	1.44E-02	0.00E+00	5.06E+03
66	1.20E+03	3.85E+03	6.88E+00	1.44E-02	0.00E+00	5.06E+03
67	4.98E+03	1.15E+04	1.33E+01	2.00E+01	0.00E+00	1.66E+04
68	2.22E+03	7.11E+03	3.80E+00	6.91E+00	9.84E+00	9.35E+03
69	6.21E+04	1.99E+05	5.31E+03	9.04E+00	0.00E+00	2.66E+05
70	3.53E+04	1.13E+05	6.01E-01	1.50E+02	2.13E+02	1.49E+05
71	3.53E+04	1.13E+05	6.01E-01	1.50E+02	2.13E+02	1.49E+05
72	4.90E+03	1.57E+04	4.62E+00	1.77E+01	2.51E+01	2.07E+04
73	3.47E+04	1.11E+05	1.12E+00	1.47E+02	2.09E+02	1.46E+05
74	8.41E+03	2.70E+04	8.10E+00	2.97E+01	4.22E+01	3.54E+04
75	3.53E+04	1.13E+05	6.01E-01	1.50E+02	2.13E+02	1.49E+05

Table 19. --continued.

Stream Order Watershed Ref. #	Fuel Use sej/m2/yr (E10)	Goods and Services sej/m2/yr (E10)	Agricultural Production sej/m2/yr (E10)	Mining Oil and Coal sej/m2/yr (E10)	Mining Other Minerals sej/m2/yr (E10)	Total Development Empower sej/m2/yr (E10)
76	1.82E+03	5.82E+03	8.25E+00	2.71E+06	9.45E+06	1.22E+07
77	3.37E+04	1.08E+05	8.91E-01	1.43E+02	2.04E+02	1.42E+05
78	3.35E+02	1.07E+03	1.10E+00	1.09E+01	0.00E+00	1.42E+03
79	1.30E+03	4.16E+03	1.28E+01	1.48E+07	5.16E+07	6.64E+07
80	3.35E+02	1.07E+03	1.10E+00	1.09E+01	0.00E+00	1.42E+03
81	1.19E+03	3.82E+03	1.14E+01	1.31E+07	4.56E+07	5.86E+07
82	3.35E+02	1.07E+03	1.10E+00	1.09E+01	0.00E+00	1.42E+03
83	3.35E+02	1.07E+03	1.10E+00	1.09E+01	0.00E+00	1.42E+03
84	1.62E+03	5.20E+03	2.12E+00	4.63E+05	1.61E+06	2.08E+06
85	8.93E+03	2.86E+04	1.91E+01	7.25E+05	2.53E+06	3.29E+06
86	1.20E+03	3.86E+03	6.88E+00	0.00E+00	0.00E+00	5.07E+03
87	8.83E+04	2.83E+05	1.07E+03	5.41E+00	0.00E+00	3.72E+05
88	1.41E+03	4.50E+03	3.34E+01	0.00E+00	0.00E+00	5.94E+03
89	2.58E+03	8.26E+03	5.00E+01	6.89E+00	0.00E+00	1.09E+04
90	2.98E+04	9.52E+04	1.57E+03	1.87E+01	4.46E+00	1.27E+05
91	5.91E+03	1.89E+04	1.45E+02	0.00E+00	0.00E+00	2.50E+04
92	5.78E+05	1.85E+06	7.05E+03	3.58E+01	0.00E+00	2.44E+06
93	0.00E+00	0.00E+00	7.93E+00	0.00E+00	0.00E+00	7.93E+00
94	3.32E+03	1.07E+04	5.24E+02	3.28E-03	0.00E+00	1.45E+04
95	3.84E+03	1.23E+04	2.53E+02	0.00E+00	0.00E+00	1.64E+04
96	1.37E+03	4.40E+03	5.25E+01	0.00E+00	0.00E+00	5.83E+03
97	6.26E+05	2.01E+06	7.65E+03	3.88E+01	0.00E+00	2.64E+06
98	3.66E+04	1.17E+05	2.83E+03	3.34E+01	7.38E+00	1.57E+05
99	5.05E+04	1.62E+05	7.58E+02	3.32E+00	0.00E+00	2.13E+05
100	0.00E+00	0.00E+00	9.17E+03	1.25E+01	0.00E+00	9.19E+03

Table 19. --continued.

Stream Order Watershed Ref. #	Fuel Use sej/m2/yr (E10)	Goods and Services sej/m2/yr (E10)	Agricultural Production sej/m2/yr (E10)	Mining Oil and Coal sej/m2/yr (E10)	Mining Other Minerals sej/m2/yr (E10)	Total Development Empower sej/m2/yr (E10)
101	1.88E+03	6.02E+03	2.51E+03	5.65E+00	0.00E+00	1.04E+04
102	9.47E+03	3.03E+04	5.81E+03	1.33E+01	0.00E+00	4.56E+04
103	1.73E+03	5.55E+03	3.04E+03	7.61E-01	0.00E+00	1.03E+04
104	1.92E+03	6.16E+03	2.35E+03	7.17E+00	0.00E+00	1.04E+04
105	1.92E+03	6.16E+03	2.35E+03	7.17E+00	0.00E+00	1.04E+04
106	1.54E+04	4.94E+04	1.36E+04	4.65E+01	0.00E+00	7.84E+04
107	1.65E+04	5.28E+04	1.00E+04	3.12E+01	0.00E+00	7.93E+04
108	1.65E+04	5.28E+04	1.47E+04	3.51E+01	0.00E+00	1.47E+04
109	2.67E+04	8.55E+04	1.40E+04	4.23E+01	0.00E+00	1.26E+05
110	3.15E+04	1.01E+05	9.20E+03	2.00E+01	0.00E+00	1.42E+05
111	7.98E+04	2.56E+05	1.74E+04	1.18E+01	0.00E+00	3.53E+05

In Figure 39, total development empower density is summarized by stream-order watershed. Development empower density decreases with stream-order watershed from 1E16 sej/yr to 1E12 sej/yr with the exception of the second-order watershed where it increases to 1.5E17 sej/yr.

Emergy of Storages

The emergy of stored biomass in forests is shown in Figure 40. Emergy of this type is not distributed in a clear longitudinal pattern in the Catatumbo drainage basin, although it is lower in the upstream watersheds. Some areas in the central region of the basin have no storage of forest biomass.

The storage organic matter in soil as emergy density is shown in Figure 41. Soil organic matter is particularly low in the Zulia and Oro Rivers. There are also areas in the drainage basin where the soil has very little to no organic matter in the soil. The majority of the drainage basin has similar storage of organic matter between 5E11 and 1E12 sej/m^2 of storged organic matter in the soil.

The map of the emergy density of stored oil and coal is similar to that of mining production of these materials because the exact distribution of the ores below ground is unknown (Figure 42). This is the same situation for the storages of clay, limestone, and phorphorus (Figure 43). In general, the storages of potential mining materials are low throughout much of the drainage basin (0-5E12 sej/m^2, but relatively high in the upper watersheds of the Catatumbo River's main channel.

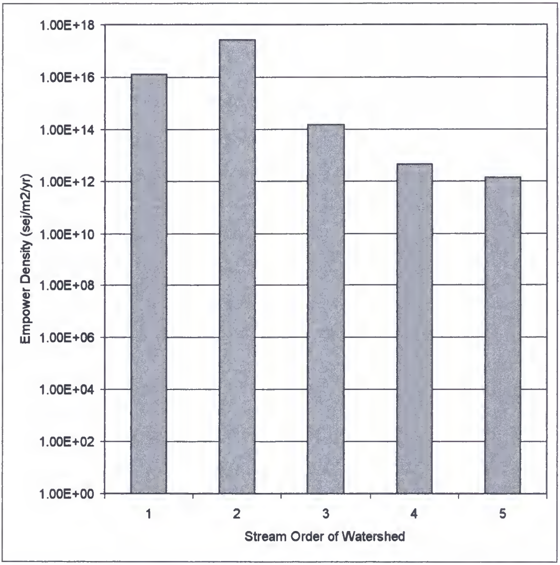


Figure 39. Total development empower density for stream order watersheds in the Catatumbo drainage basin.

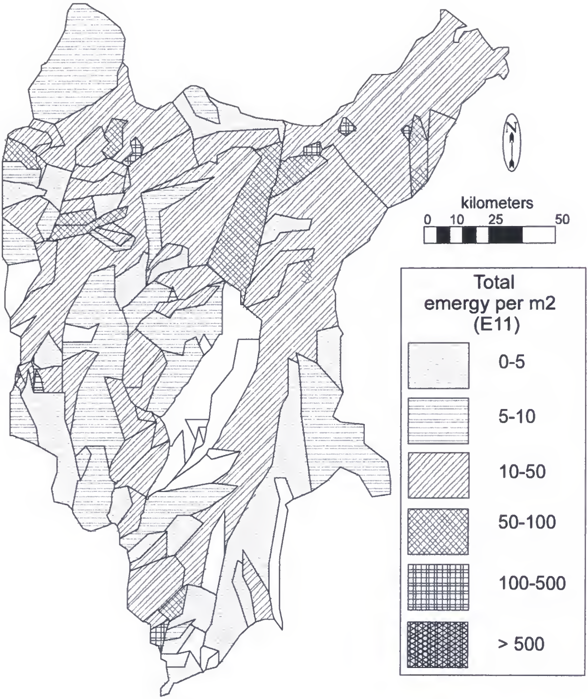


Figure 40. Total biomass storage as emergy per m2 iin stream order watersheds of the Catatumbo River drainage basin.

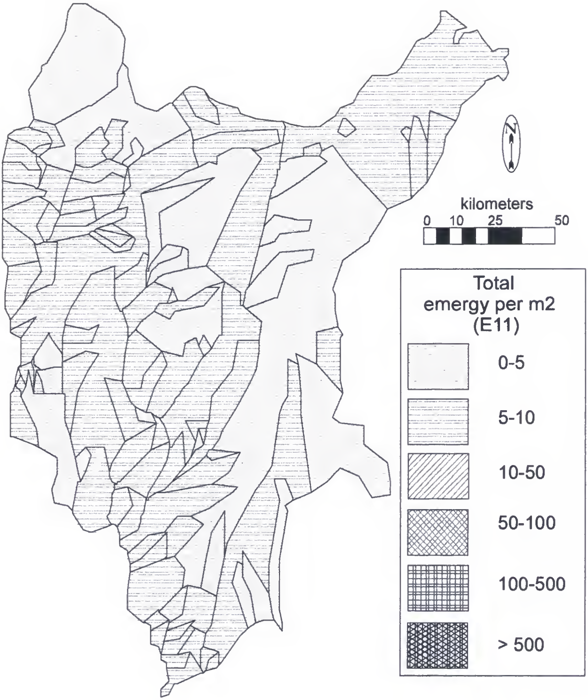


Figure 41. Storage of organic matter in soil as emergy per m2 in stream order watersheds of the Catatumbo River drainage basin.

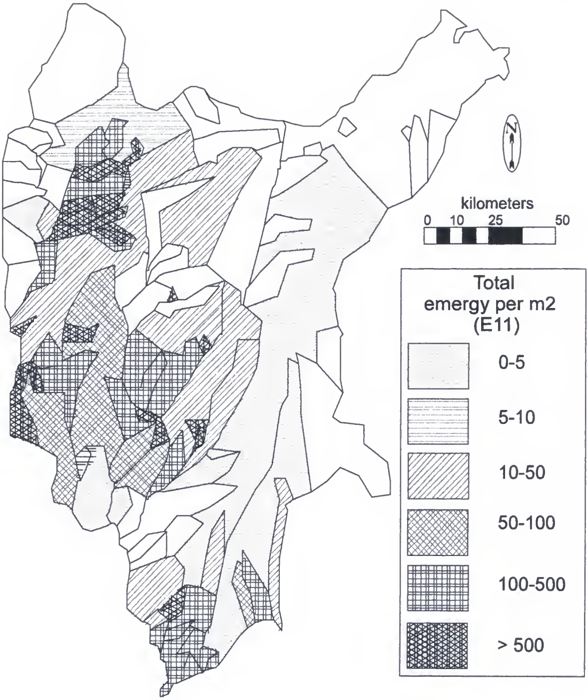


Figure 42. Storage of oil and coal as emergy per m2 in stream order watersheds of the Catatumbo River drainage basin.

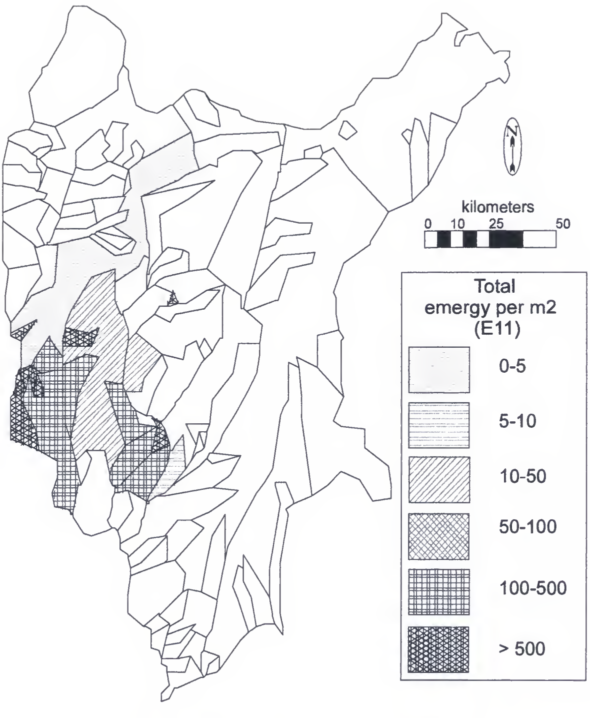


Figure 43. Storage of clay, limestone, and phosphorus as emergy per m2 in stream order watersheds of the Catatumbo River drainage basin.

The total emergy density of storages in the Catatumbo drainage basin is shown in Figure 44. Emergy density is high in the upper watersheds of the basin, but in the central and lower regions the emergy density of the storages is decreased. A summary of emergy density of all the storages for each stream-order watershed is given in Table 20.

The graphs in Figure 45 show the average emergy density by stream-order watershed for storages in the Catatumbo drainage basin. The average storage of biomass in forests is relatively higher in the fourth and fifth-order watersheds (5E12 and 3E12 sej/m^2, respectively). In the remainder of the drainage basin the average storage of biomass is between the narrow range of 1E12-1.6E12 sej/m^2.

The majority of the drainage basin has similar average storage of organic matter between 5E11 and 8E11 sej/m^2 of storged organic matter in the soil. The average storage of oil and coal decreases with stream-order watershed (5E13 to1.3E12 sej/m^2). The average storage of other mining materials is highest in the second-order watershed (5.5E13 sej/m^2). No storage of potential mining materials are found in the fourth or fifth-order watersheds.

The total average density of stored emergy decreases from the first to the third-order watersheds (1.6E14-3.6E12 sej/m^2). Average emergy density of all storages increases in the fourth-order watershed (5.8E12 sej/m^2), and decreases again in the fifth-order watershed (3.8E12 sej/m^2).

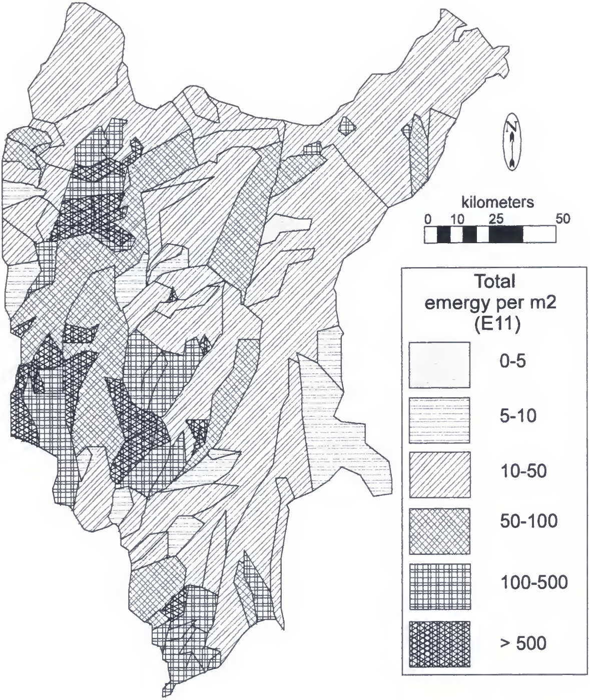


Figure 44. Total storage as emergy per m2 in stream order watersheds of the Catatumbo River drainage basin.

Table 20. Summary of emergy density storages in the Catatumbo drainage basin.

Stream Order Watershed Ref. #	Biomass in Forests[1] sej/m2 (E10)	Organic Matter in Soil[2] sej/m2 (E10)	Minerals Oil and Coal[3] sej/m2 (E10)	Mining Other Minerals[3] sej/m2 (E10)	Total[4] Storage sej/m2 (E10)
2	91.47	33.51	0.00	0.00	124.98
3	301.26	78.53	0.00	0.00	377.71
4	210.28	49.29	88.92	0.00	348.49
5	74.29	86.09	0.00	0.00	160.38
6	33.42	86.10	0.00	0.00	119.52
7	102.92	86.10	0.00	0.00	204.72
8	704.68	47.84	0.07	0.00	209.42
9	550.52	100.04	1407.97	0.00	2058.53
10	2210.23	86.11	0.00	0.00	2296.34
11	232.04	99.09	0.00	0.00	331.14
12	283.47	99.46	1202.37	0.00	1585.30
13	2210.23	86.11	0.00	0.00	2296.34
14	453.28	71.94	0.00	0.00	525.21
15	192.36	64.35	280.27	40.17	577.16
16	113.71	51.49	0.00	0.00	165.20
17	566.11	76.48	0.00	0.00	642.59
18	2229.80	32.56	13141.88	0.00	15404.25
19	458.29	100.06	0.00	0.00	558.35
20	608.44	60.89	0.00	0.00	669.33
21	2210.23	86.13	0.00	0.00	2296.36
22	155.68	86.10	0.00	0.00	204.72
23	137.40	39.68	242.48	0.00	419.56

Table 20. --continued.

Stream Order Watershed Ref. #	Biomass in Forests[1] sej/m2 (E10)	Organic Matter in Soil[2] sej/m2 (E10)	Minerals Oil and Coal[3] sej/m2 (E10)	Mining Other Minerals[3] sej/m2 (E10)	Total[4] Storage sej/m2 (E10)
24	458.29	100.07	0.00	0.00	558.36
25	690.73	78.53	0.00	0.00	377.71
26	160.79	77.42	6604.32	0.00	6842.53
27	92.03	76.57	0.00	0.00	168.60
28	40.69	84.68	0.00	0.00	125.37
29	87.98	84.77	0.00	0.00	172.75
30	309.13	76.20	1867.81	0.00	2253.14
31	63.71	42.82	0.00	0.00	106.54
32	26.60	53.42	0.00	0.00	80.02
33	10.70	71.80	5786.95	0.00	5869.44
34	311.89	51.66	40.29	0.00	403.85
35	113.01	51.36	7741.65	0.00	7906.02
36	63.11	66.45	172.22	0.00	301.77
37	741.48	62.82	5096.89	0.00	5901.19
38	732.90	61.82	10799.61	0.00	11594.33
39	3.12	35.94	0.00	0.00	39.07
40	86.89	50.36	0.00	0.00	137.25
41	108.78	100.15	8483.41	0.00	8692.35
42	265.49	100.16	18188.90	0.00	18554.55
43	88.87	79.23	2750.04	0.00	2308.17
44	108.07	75.41	2121.60	0.00	2305.07
45	388.16	41.23	0.00	0.00	429.39

Table 20. --continued.

Stream Order Watershed Ref. #	Biomass in Forests[1] sej/m2 (E10)	Organic Matter in Soil[2] sej/m2 (E10)	Minerals Oil and Coal[3] sej/m2 (E10)	Mining Other Minerals[3] sej/m2 (E10)	Total[4] Storage sej/m2 (E10)
46	43.00	46.42	0.00	0.00	89.43
47	127.28	46.77	0.00	0.00	661.87
48	2.45	55.92	0.00	0.00	58.37
49	0.00	68.45	0.00	0.00	68.45
50	167.70	45.61	0.00	0.00	213.31
51	69.39	58.49	568.89	159.81	856.58
52	87.64	70.67	0.00	0.00	158.31
53	64.83	34.61	115.56	0.00	215.00
54	0.00	56.86	316.55	0.00	373.41
55	347.54	72.11	0.00	0.00	419.65
56	0.00	623.73	36708.31	9625.46	454508.35
57	0.00	623.73	36708.31	9625.46	454508.35
58	0.00	623.73	36708.31	9625.46	454508.35
59	2.17	61.71	0.00	0.00	63.88
60	314.72	57.18	2692.39	240.24	3304.53
61	8.90	40.19	3847.35	4548.40	8444.84
62	0.00	76.79	13802.14	0.00	13878.93
63	97.78	59.20	1438.09	0.00	1595.07
64	0.00	57.63	476.31	0.00	533.94
65	124.64	55.51	4932.23	1305.30	6417.68
66	170.89	67.70	2847.79	0.00	3086.38
67	52.27	35.41	0.00	0.00	87.68

Table 20. --continued.

Stream Order Watershed Ref. #	Biomass in Forests[1] sej/m2 (E10)	Organic Matter in Soil[2] sej/m2 (E10)	Minerals Oil and Coal[3] sej/m2 (E10)	Mining Other Minerals[3] sej/m2 (E10)	Total[4] Storage sej/m2 (E10)
68	0.00	55.03	150866.01	259028.56	409949.60
69	38.39	51.14	15.66	0.00	105.20
70	243.29	53.76	68948.26	118380.34	187625.65
71	1320.27	50.27	319899.80	549250.20	870520.55
72	104.71	41.93	1409.79	2420.53	3976.96
73	0.00	62.79	94774.16	162721.96	257558.91
74	42.67	46.51	883.35	1516.66	2489.20
75	160.07	63.59	184349.99	6512.02	191085.67
76	481.82	58.77	1887.16	2705.77	5133.52
77	67.32	61.67	14629.16	25117.45	39875.59
78	316.06	49.90	14692.02	0.00	15057.99
79	144.53	59.70	6225.01	13897.75	20326.98
80	0.00	60.76	12256.66	0.00	12317.42
81	350.43	62.32	636.21	4313.08	5362.04
82	0.00	42.35	24953.32	0.00	24995.66
83	0.00	61.92	45218.18	0.00	45280.10
84	0.00	62.32	1668.82	92.74	1823.87
85	253.22	57.72	562.49	3569.70	4443.14
86	58.35	30.23	0.00	0.00	88.57
87	81.00	54.72	0.00	0.00	88.57
88	0.00	54.01	0.12	0.00	54.13
89	0.00	54.01	0.12	0.00	54.13

Table 20. --continued.

Stream Order Watershed Ref. #	Biomass in Forests[1] sej/m2 (E10)	Organic Matter in Soil[2] sej/m2 (E10)	Minerals Oil and Coal[3] sej/m2 (E10)	Mining Other Minerals[3] sej/m2 (E10)	Total[4] Storage sej/m2 (E10)
90	0.00	40.37	129.04	0.00	169.40
91	65.49	62.15	0.00	0.00	127.63
92	8.68	63.44	2.02	0.00	73.82
93	105.81	63.35	0.00	0.00	169.16
94	0.00	33.12	103.43	0.00	136.55
95	3.06	62.60	0.00	0.00	65.66
96	36.39	65.34	0.00	0.00	101.73
97	153.30	53.27	0.00	0.00	206.57
98	108.46	45.05	4700.29	0.00	4853.80
99	332.54	54.44	236.04	0.00	623.02
100	3.27	32.59	815.84	0.00	851.70
101	905.32	60.79	14003.45	0.00	14969.56
102	40.79	59.17	1741.07	0.00	1841.03
103	361.39	63.57	449.18	0.00	874.13
104	1488.12	78.07	2974.34	0.00	4540.52
105	95.88	57.70	4038.42	0.00	4192.01
106	30.63	67.42	2678.68	0.00	2776.73
107	0.00	56.01	1587.71	0.00	1643.72
108	0.00	62.72	3683.04	0.00	3745.76
109	0.00	61.23	4761.72	0.00	4822.94
110	0.00	73.25	3152.08	0.00	3225.33
111	0.81	61.67	1645.29	0.00	1707.77

Emergy of Water

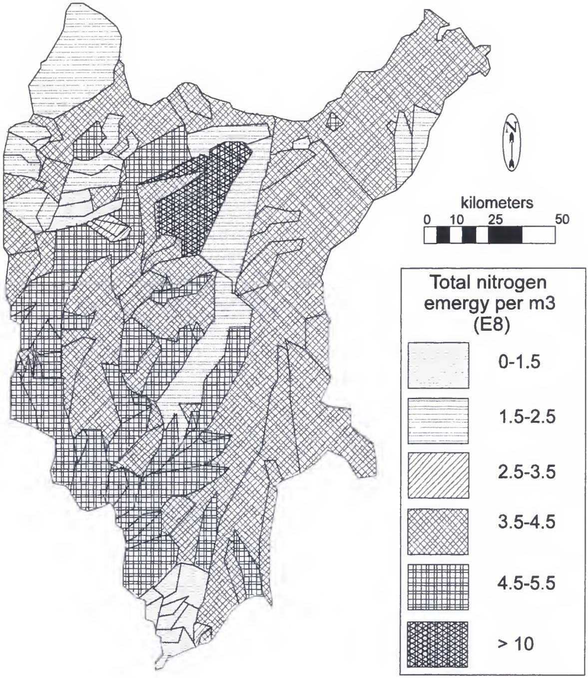
In this section, the results for emergy of river constituents per volume of river water at the scale of the river and the emergy of water, exclusive of constituents, at the scale of the watershed are given.

Emergy of constituents in river water

The spatial distribution of total nitrogen as emergy per volume of river water is shown in the map Figure 46. Throughout most of the drainage basin, the emergy of total nitrogen per volume of river water is between 3.5E8 and 5.5E8 sej/m^3. In some watersheds of the River Tarra, total nitrogen drops to within 1.5E8-2.5E8 sej/m^3, but also increases in the same river to over 1E9 sej/m^3. The range of total nitrogen as emergy per volume in river water is relatively narrow and is within less than a factor of two (1-1.5E8 sej/m^3).

In Figure 47, the spatial distribution of total phosphorus as emergy per volume in river water is presented. Total phosphorus is highest in the extreme upper watersheds, in the main channel of the Catatumbo River, and in the lower watersheds nearest Lake Maracaibo. In general, emergy of total phosphorus per volume of river water is between 6E8-9E8sej/m^3 throughout much of the drainage basin. The range of total phosphorus, however, is between 3E8 and 4E9 sej/m^3.

A summary of the average emergy water of total nitrogen and total phosphorus per volume in river for the stream-order watersheds is given in Figure 48. The average emergy of total nitrogen per m^3 remains relatively the same for each stream-order watershed with little variation. In contrast, the


N
kilometers
0 10 25 50
Total nitrogen emergy per m3 (E8)
0-1.5
1.5-2.5
2.5-3.5
3.5-4.5
4.5-5.5
> 10

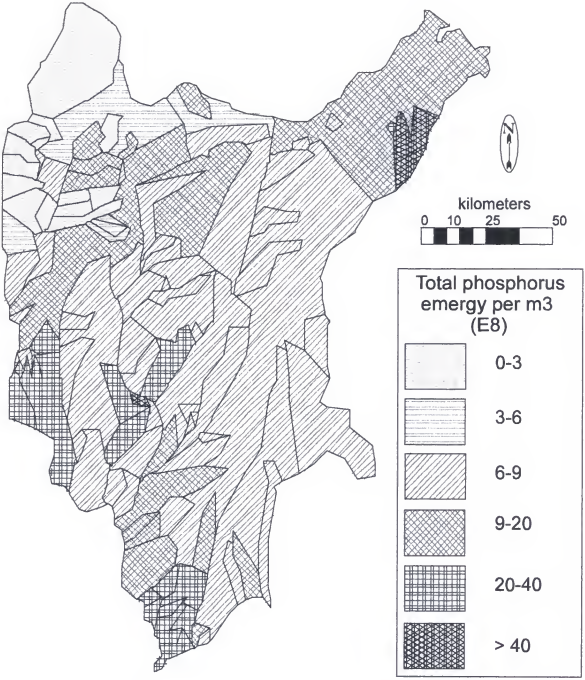


Figure 50. Total phosphorus emergy per m3 river water in stream order watersheds of the Catatumbo River drainage basin.

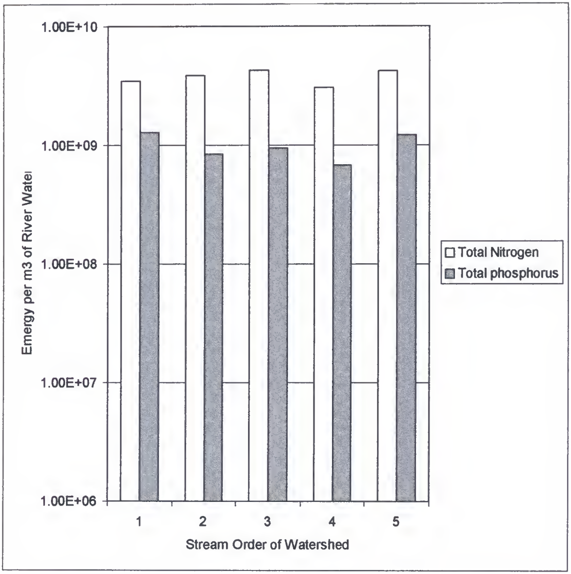


Figure 51. Total nitrogen and total phosphorus as emergy per m3 of river water in stream order watersheds of the Catatumbo drainage basin.

average emergy of total phosphorus per m^3 generally decreases from the first-order watersheds to the fourth-order watersheds. In the fifth-order watershed, average total phosphorus increases to nearly that of the first-order watersheds.

The emergy of sediments per volume of river water increases in a longitudinal downstream pattern as shown in Figure 49. The range of emergy of river sediments per volume is wide (less than 1E10-more than 5E13 sej/m^3). A section of the northern most area of the drainage basin and the watersheds comprising the floodplain areas have the most emergy of river sediment per volume of river water (averaging more than 5E13 sej/m^3).

The average emergy of river sediments per volume of river water (Figure 50) generally increases with watershed stream-order with the exception of the fourth-order watershed where there is a decrease of nearly 5E13 sej/m^3. The range of the average emergy per volume of river sediments is wide beginning at 1.5E11 sej/m^3 at the uppermost segments, and increasing to 5E14 sej/m^3 in the fifth-order watershed.

Because oil spills have occurred only in the third and fourth-order watersheds, the emergy of spilled oil per volume of river water is limited to those areas (Figure 51). However, a decrease in emergy per volume is detectable.

The average emergy of spilled oil per volume is shown in Figure 52. The emergy of oil per volume of river water decreases in magnitude from the third to the fourth-order watersheds.

In Figure 53, the spatial distribution of the total emergy of the water quality constituents per volume of river water is shown. Emergy per volume is largest (>

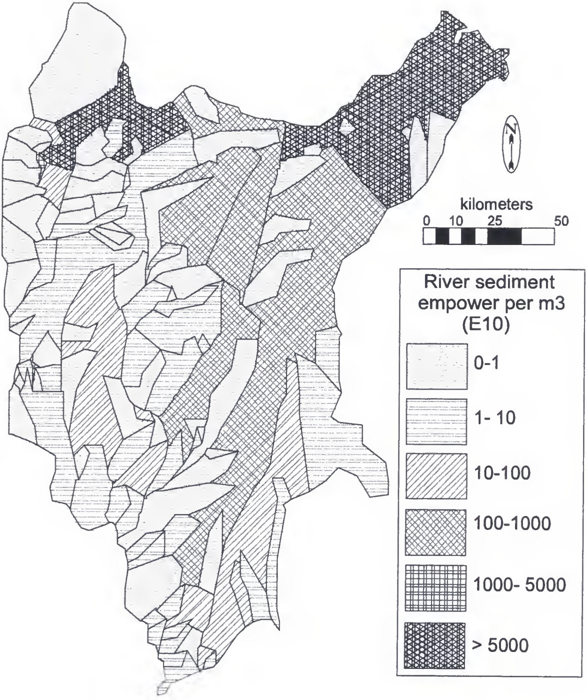


Figure 52. River sediments as empower per m3 in stream order watersheds of the Catatumbo River drainage basin.

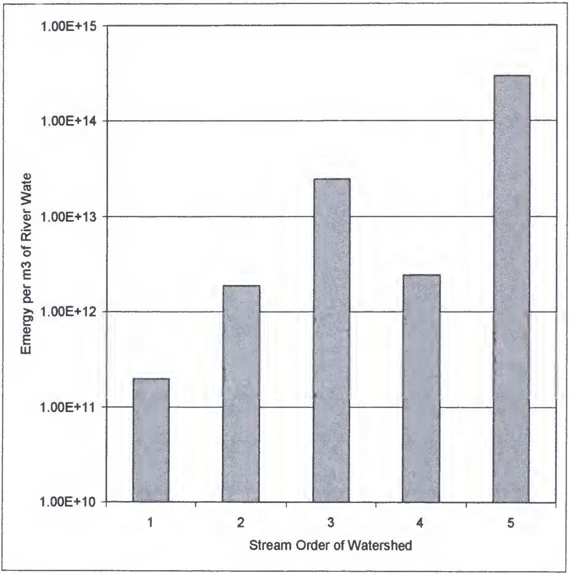


Figure 53. River sediments as emergy per m3 of river water in stream order watersheds of the Catatumbo drainage basin.

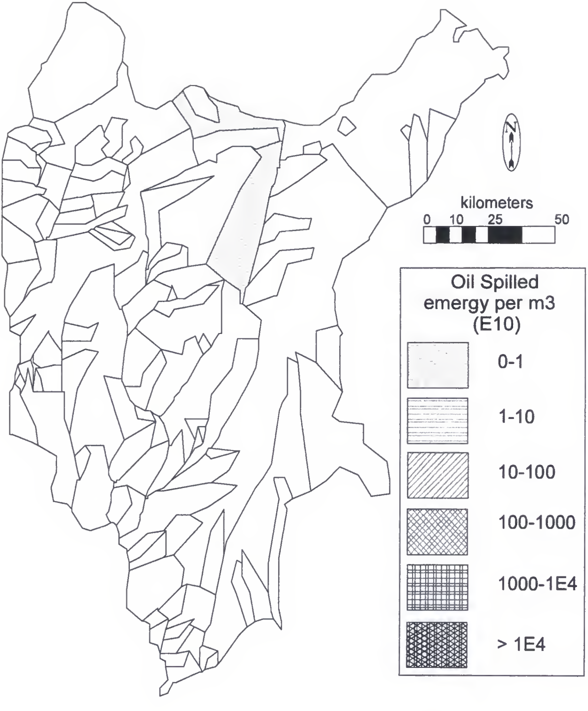


Figure 54. Oil spilled (minus that recovered) emergy per m3 river water in stream order watersheds of the Catatumbo River drainage basin.

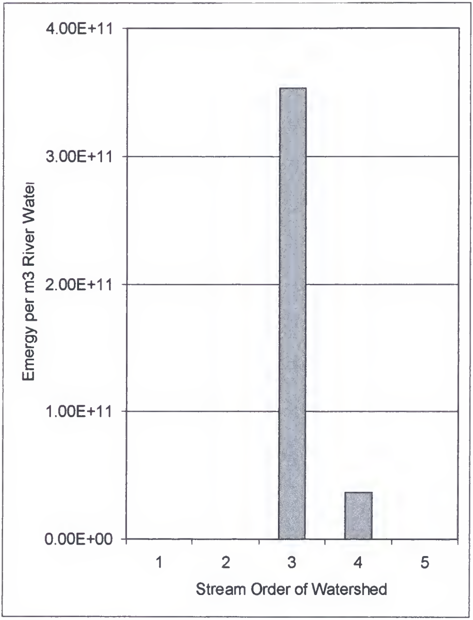


Figure 55. Oil spilled as emergy per m3 in stream order watersheds of the Catatumbo drainage basin.

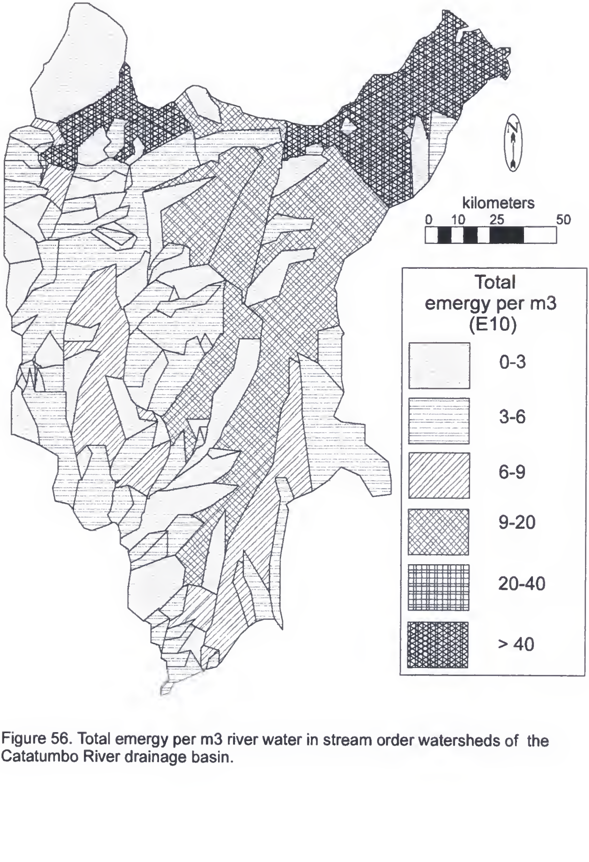


Figure 56. Total emergy per m3 river water in stream order watersheds of the Catatumbo River drainage basin.

5E13 sej/m^3) in the northern areas of the drainage basin (River Oro and areas of the main channel of the Catatumbo River) and in the lower watersheds near Lake Maracaibo. A summary of the emergy of the river water constituents per volume of river water for all of the river water constituents in each stream-order watershed is given in Table 21.

A clear trend in the total emergy of river constituents per volume of river water by stream-order watershed is shown in Figure 54. Total emergy of river constituents per volume increases by approximately one magnitude for each stream-order watershed from 2.8E11 sej/m3 in the first-order watersheds to 2.3E15 sej/m^3 in the fifth-order watersheds. However, between the third and fourth-order watersheds total emergy per volume decreases by approximately 2E14 sej/m^3.

No map was created of the spatial distribution of river water chemical potential per m^3 because the range of the emergy per volume throughout the drainage basin was very narrow (2.27E11-2.35E11 sej/m^3). However, in Figure 55, the average chemical potential in river water is shown to decrease with stream-order watershed up to the fourth-order watersheds where the emergy per volume is 2.31E11 sej/m^3). After that point, the emergy per volume of chemical potential increases to that of the first-order watersheds (2.34E11 sej/m^3).

Emergy of water at the watershed scale

The emergy of water (exclusive of river constituents) of the river at the watershed scale (sej/m^3) compared to the emergy of river constituents per

Table 21. Summary of water quality as emergy per m3 in the Catatumbo drainage basin.

Stream Order Watershed Ref. #	Total Nitrogen sej/m3 (E8)	Total Phosphorus sej/m3 (E8)	River Sediments sej/m3 (E8)	Oil Spilled sej/m3 (E8)	Total Emergy Volume sej/m3 (E8)
2	1.51E+01	1.70E+00	1.25E+00	0.00E+00	1.81E+01
3	4.21E+01	1.21E+01	2.30E+07	3.52E+00	2.30E+07
4	4.47E+01	5.35E+00	1.29E+07	0.00E+00	1.29E+07
5	4.02E+01	9.95E+00	1.30E+01	0.00E+00	9.40E+01
6	4.47E+01	5.35E+00	6.27E+05	3.09E+00	6.28E+05
7	1.96E+01	5.20E+01	6.78E+00	0.00E+00	1.42E+03
8	1.96E+01	5.20E+01	6.37E-01	0.00E+00	7.22E+01
9	1.54E+01	1.82E+00	5.10E+03	0.00E+00	5.12E+03
10	4.63E+01	1.41E+01	1.56E+03	0.00E+00	1.62E+03
11	4.00E+01	0.00E+00	2.87E+04	0.00E+00	2.88E+04
12	4.62E+01	1.41E+01	2.32E+01	0.00E+00	4.61E+02
13	3.66E+01	2.79E+01	4.48E+02	0.00E+00	9.85E+02
14	1.51E+01	1.70E+00	1.08E+01	0.00E+00	1.62E+03
15	4.90E+01	1.46E+01	9.44E+03	0.00E+00	9.52E+03
16	1.96E+01	7.95E+00	9.77E+02	0.00E+00	1.85E+03
17	1.51E+01	1.70E+00	2.39E+02	0.00E+00	3.10E+03
18	1.51E+01	1.07E+01	7.92E+01	0.00E+00	1.05E+02
19	1.51E+01	1.70E+00	5.34E+01	0.00E+00	1.02E+03
20	1.96E+01	7.95E+00	2.17E+05	3.96E+00	2.17E+05
21	1.71E+01	7.25E+00	1.04E+02	0.00E+00	3.36E+03
22	4.15E+01	6.00E+00	2.22E+05	0.00E+00	2.22E+05
23	1.08E+02	1.63E+01	1.18E+05	0.00E+00	1.19E+05

Table 21. --continued.

Stream Order Watershed Ref. #	Total Nitrogen sej/m3 (E8)	Total Phosphorus sej/m3 (E8)	River Sediments sej/m3 (E8)	Oil Spilled sej/m3 (E8)	Total Emergy Volume sej/m3 (E8)
24	4.00E+01	6.00E+00	1.60E+06	0.00E+00	1.60E+06
25	4.15E+01	6.00E+00	6.68E+00	0.00E+00	5.42E+01
26	1.51E+01	9.85E+00	8.82E+02	0.00E+00	3.49E+03
27	1.51E+01	1.70E+00	6.22E+00	0.00E+00	1.43E+03
28	4.00E+01	6.00E+00	3.59E+04	0.00E+00	3.66E+04
29	4.00E+01	6.00E+00	9.61E+03	0.00E+00	9.65E+03
30	1.51E+01	9.80E+00	1.15E+02	0.00E+00	2.48E+02
31	4.06E+01	7.10E+00	1.32E+02	0.00E+00	1.80E+02
32	4.00E+01	1.70E+00	0.00E+00	0.00E+00	4.12E+03
33	4.00E+01	1.70E+00	0.00E+00	0.00E+00	4.17E+01
34	1.51E+01	1.70E+00	8.32E+02	0.00E+00	8.49E+02
35	1.09E+01	1.05E+00	5.96E+02	0.00E+00	1.82E+03
36	1.51E+01	1.70E+00	6.48E+01	0.00E+00	4.27E+03
37	1.20E+01	1.06E+00	1.02E+03	0.00E+00	1.04E+03
38	1.08E+01	8.75E-01	1.64E+02	0.00E+00	2.72E+02
39	4.15E+01	6.00E+00	5.17E+02	0.00E+00	4.56E+03
40	4.04E+01	5.82E+00	1.39E+01	0.00E+00	6.02E+01
41	2.53E+01	3.28E+00	2.80E+02	0.00E+00	3.08E+02
42	2.95E+01	3.99E+00	7.77E+02	0.00E+00	2.93E+03
43	3.15E+01	4.33E+00	1.64E+01	0.00E+00	5.23E+01
44	4.00E+01	6.00E+00	7.55E+03	0.00E+00	7.59E+03
45	4.15E+01	6.00E+00	1.01E+03	0.00E+00	1.06E+03

Table 21. --continued.

Stream Order Watershed Ref. #	Total Nitrogen sej/m3 (E8)	Total Phosphorus sej/m3 (E8)	River Sediments sej/m3 (E8)	Oil Spilled sej/m3 (E8)	Total Emergy Volume sej/m3 (E8)
46	4.15E+01	6.00E+00	1.80E+02	0.00E+00	2.27E+02
47	4.15E+01	6.00E+00	1.12E+01	0.00E+00	5.88E+01
48	4.15E+01	6.00E+00	1.95E+02	0.00E+00	2.43E+02
49	4.15E+01	6.00E+00	2.84E+02	0.00E+00	3.32E+02
50	4.00E+01	6.00E+00	7.03E+01	0.00E+00	1.16E+02
51	4.00E+01	6.00E+00	1.23E+04	0.00E+00	1.24E+04
52	4.15E+01	6.00E+00	1.79E+03	0.00E+00	1.84E+03
53	4.00E+01	6.00E+00	3.45E+03	0.00E+00	3.49E+03
54	1.95E+01	7.95E+00	7.31E+05	0.00E+00	7.31E+05
55	4.57E+01	7.10E+00	1.35E+03	0.00E+00	1.41E+03
56	4.57E+01	7.10E+00	3.46E+01	0.00E+00	8.74E+01
57	4.57E+01	7.10E+00	2.70E+02	0.00E+00	3.23E+02
58	4.57E+01	7.10E+00	1.99E+02	0.00E+00	2.52E+02
59	4.15E+01	6.00E+00	5.17E+03	0.00E+00	5.21E+03
60	4.57E+01	7.10E+00	7.75E+03	0.00E+00	7.80E+03
61	4.57E+01	2.29E+01	8.80E+00	0.00E+00	7.74E+01
62	4.57E+01	7.10E+00	2.78E+03	0.00E+00	2.84E+03
63	4.56E+01	2.29E+01	1.96E+03	0.00E+00	2.03E+03
64	4.57E+01	7.10E+00	8.99E+02	0.00E+00	9.51E+02
65	4.15E+01	6.00E+00	5.66E+02	0.00E+00	6.13E+02
66	4.16E+01	6.22E+00	6.82E+02	0.00E+00	7.29E+02
67	4.15E+01	6.00E+00	1.42E+03	0.00E+00	1.47E+03

Table 21. --continued.

Stream Order Watershed Ref. #	Total Nitrogen sej/m3 (E8)	Total Phosphorus sej/m3 (E8)	River Sediments sej/m3 (E8)	Oil Spilled sej/m3 (E8)	Total Emergy Volume sej/m3 (E8)
68	4.00E+01	6.00E+00	2.72E+05	0.00E+00	2.72E+05
69	4.00E+01	6.00E+00	3.45E+04	0.00E+00	3.45E+04
70	4.00E+01	6.00E+00	5.67E+03	0.00E+00	5.72E+03
71	4.56E+01	2.29E+01	8.34E+02	0.00E+00	9.02E+02
72	4.56E+01	2.29E+01	3.56E+03	0.00E+00	3.62E+03
73	4.56E+01	2.29E+01	2.10E+02	0.00E+00	2.78E+02
74	4.55E+01	2.27E+01	6.16E+03	0.00E+00	6.22E+03
75	4.56E+01	2.29E+01	4.84E+02	0.00E+00	5.52E+02
76	4.56E+01	2.29E+01	2.30E+02	0.00E+00	2.99E+02
77	4.56E+01	2.29E+01	7.88E+01	0.00E+00	1.47E+02
78	4.56E+01	4.49E+01	3.07E+04	0.00E+00	3.08E+04
79	4.00E+01	6.00E+00	2.91E+02	0.00E+00	3.37E+02
80	4.00E+01	6.00E+00	6.86E+02	0.00E+00	7.32E+02
81	4.56E+01	2.29E+01	5.83E+03	0.00E+00	5.90E+03
82	4.57E+01	7.10E+00	7.11E+03	0.00E+00	7.17E+03
83	4.57E+01	7.10E+00	6.62E+02	0.00E+00	7.15E+02
84	4.88E+01	1.28E+01	3.11E+03	0.00E+00	3.17E+03
85	4.00E+01	7.10E+00	4.60E+04	0.00E+00	4.60E+04
86	4.57E+01	7.10E+00	2.24E+02	0.00E+00	2.76E+02
87	4.57E+01	7.36E+00	3.09E+03	0.00E+00	3.15E+03
88	4.57E+01	7.10E+00	4.32E+02	0.00E+00	4.84E+02
89	4.57E+01	7.10E+00	5.37E+02	0.00E+00	5.90E+02

Table 21. --continued.

Stream Order Watershed Ref. #	Total Nitrogen sej/m3 (E8)	Total Phosphorus sej/m3 (E8)	River Sediments sej/m3 (E8)	Oil Spilled sej/m3 (E8)	Total Emergy Volume sej/m3 (E8)
90	4.16E+01	6.00E+00	2.50E+03	0.00E+00	2.55E+03
91	4.88E+01	1.28E+01	5.11E+02	0.00E+00	5.73E+02
92	4.57E+01	7.10E+00	7.89E+03	0.00E+00	7.94E+03
93	4.59E+01	7.55E+00	1.87E+03	0.00E+00	1.93E+03
94	4.88E+01	1.28E+01	8.82E+02	0.00E+00	8.15E+02
95	4.00E+01	7.10E+00	1.14E+03	0.00E+00	1.19E+03
96	4.88E+01	1.28E+01	1.37E+03	0.00E+00	1.43E+03
97	4.88E+01	1.28E+01	1.58E+03	0.00E+00	1.64E+03
98	4.88E+01	1.28E+01	4.78E+03	0.00E+00	4.84E+03
99	4.88E+01	1.28E+01	8.08E+02	0.00E+00	8.70E+02
100	4.15E+01	6.00E+00	2.03E+04	0.00E+00	2.03E+04
101	1.00E+01	2.30E+01	4.12E+03	0.00E+00	4.15E+03
102	1.00E+01	2.30E+01	4.76E+04	0.00E+00	4.76E+04
103	9.73E+00	3.60E+01	2.00E+03	0.00E+00	1.97E+03
104	9.80E+00	3.63E+01	2.83E+03	0.00E+00	2.87E+03
105	9.80E+00	3.63E+01	1.45E+03	0.00E+00	1.49E+03
106	9.80E+00	3.63E+01	1.06E+03	0.00E+00	1.10E+03
107	9.80E+00	3.63E+01	0.00E+00	0.00E+00	4.61E+01
108	3.31E+01	1.40E+01	2.23E+04	0.00E+00	2.23E+04
109	4.15E+01	6.00E+00	5.67E+03	0.00E+00	5.71E+03
110	1.02E+01	3.58E+01	1.63E+03	0.00E+00	1.68E+03
111	9.80E+00	3.63E+01	1.62E+03	0.00E+00	1.68E+03

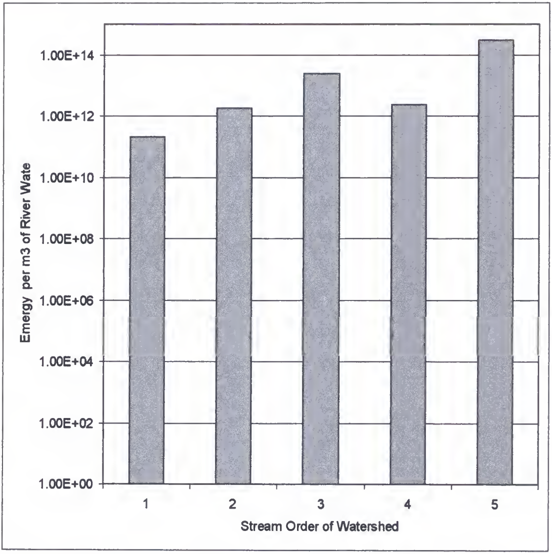


Figure 54. Water quality emergy (exclusive of water itself) per m3 of river water for stream order watersheds in the Catatumbo drainage basin.

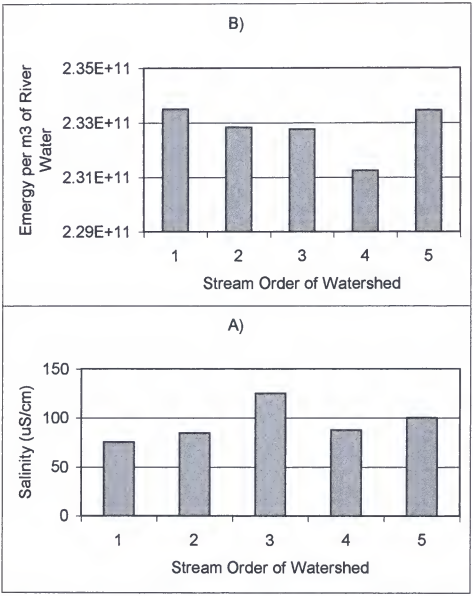


Figure 55. Graph showing A) average salinty for the stream order watersheds and B) average chemical potential per volume of river water in the Catatumbo drainage basin.

volume of river water is shown in Figure 56. Emergy of the water per cubic meter, exclusive of constituents, increases from the first- to the third-order watersheds. At the fourth-order watershed, the emergy of the water drops significantly, and then increases again in the fifth-order watershed to reach its highest level.

Transport ratio of emergy in river water

In Figure 57, a summary of the transport ratios for each constituent of water quality is presented. In graph A, the average geo-potential emergy for each stream-order watershed increases by three orders of magnitude, from 9E18 sej in the first-order watersheds to 4E21 sej in the fifth-order watersheds. In contrast, the geo-potential emergy in the third and fourth-order watersheds [are relatively close vary only within a factor of two, 4.8E20 sej and 8.4E20 sej, respectively.

In graph B, the emergy of the constituents of river water are given. The emergy of total nitrogen generally increases with stream-order watershed from 1.1E18 to 3.4E18 sej with a decrease in the second-order watersheds (3.6E17 sej). Total phosphorus does not have a clear trend with respect to stream-order watershed, but it is highest in the fourth- and fifth-order watersheds, 1.3E18 and 9.8E17 sej, respectively . Spilled oil in the third and fourth-order has the highest total emergy (1.4E20 sej and 7.8E19 sej, respectively) of the constituents of river water in the drainage basin.

Graph C shows the transport ratios for each of the constituents of river water. The transport ratios for total nitrogen and total phosphorus generally

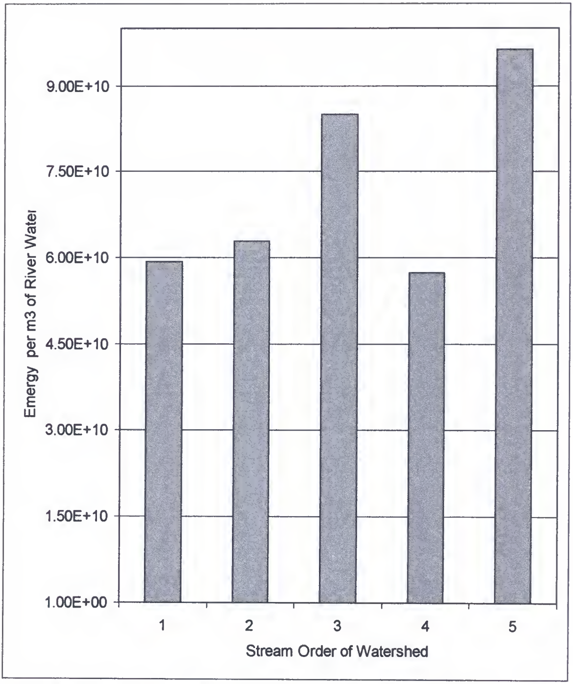


Figure 56. Emergy of water, exclusive of constituents, per m3 of river water for at stream order watersheds stream order watersheds the watershed scale in the Catatumbo drainage basin.

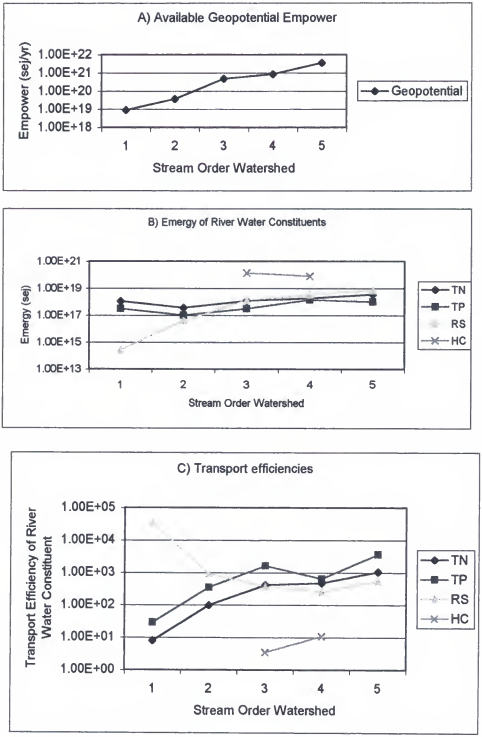


Figure 57. A) Available geopotential empower by stream order watershed; B) emergy of various river water constituents;
C) transport efficiencies for each of the river water constituents.
(TN = total nitrogen; TP = total phosphorus; RS = river sediments;
HC = hydrocarbons from spilled oil.

increase with stream-order watershed with the exception of a drop in the transport ratio of total phosphorus in the fourth-order watershed. The transport ratio for total nitrogen increases from 7.9 in the first-order watershed to 1040 in the fifth-order watershed. The transport ratio for total phosphorus ranges from 28.7 in the first-order watershed to 3638 in the fifth-order watershed.

In contrast, the transport ratio of river sediments decreases with stream-order watershed. The greatest decrease is between the first- and second-order watersheds, which drops from a transport ratio of 34105 to 907. The transport ratio for oil triples between the third and fourth-order watersheds from 3.5 to 10.7.

Population Density and Road Length

An estimate of the average population density of the stream-order watersheds is given in Figure 58. There is no clear trend of the population density with stream-order watershed. However, population density in the first, second, and third-order watersheds (25-32 per/km^2) is much higher than in the fourth and fifth-order watersheds (3-4 per/km^2).

The total length of principle roads (paved and unpaved) for each stream-order watershed is given in Figure 59. The road length in the first, fourth and fifth stream-order watersheds averages 14 km. In the second-order watershed, road length increases to 26 km. The longest road length is in the third-order watershed where the length reaches 78 km.

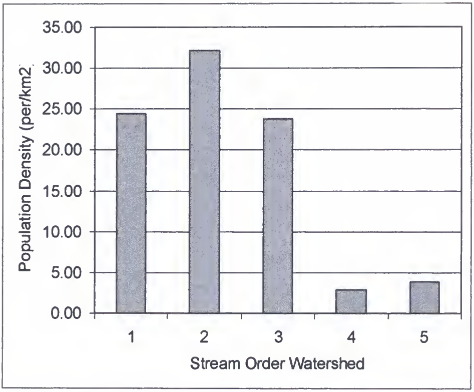


Figure 58. Estimate of population density by stream order watershed.

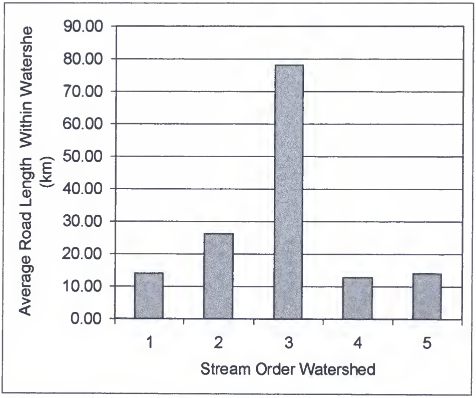


Figure59. Average road length in stream order watersheds of the Catatumbo drainage basin.

DISCUSSION

This chapter of the dissertation is divided into five sections. The first section is a review of the results of the study, which includes the emergy analyses at the national and regional scales and spatial analyses of emergy. The next section introduces ideas of how the results of this study may have been different if certain attributes of the drainage basin or some of its watersheds were different. Then, a section on how the results of this study may have been different if various plans for development, which were actually scheduled, were to have taken place. In the fourth section, given the results of this study, alternative policies for managing the drainage basin are recommended.

A major hindrance to completing this study was the difficulty of obtaining information and scarcity of data. For this reason, a final section suggesting ways to improve a future study such as this one is included.

Results of this Study

Emergy Analyses

The emergy analyses performed in this study provide an overview of the general organization of the larger scale systems of which the Catatumbo River drainage basin is a part. The most important aspect of the emergy analyses is that some aspects of the organization of the drainage basin can be inferred, but all the results must be considered to get a clear picture of the drainage basin.

The systems diagrams of Venezuela and Colombia (Figures 9 and 10) show that the countries are very similar in their overall organization. The major differences of the general geography of the two countries is that Venezuela has the large lake called Lake Maracaibo. Colombia does not have a similar geographic feature. In addition, Venezuela has a larger expanse of lowlands, or llanos, than Colombia. Colombia has more mountainous regions and greater coverage of tropical rain forest.

Overall, Venezuela and Colombia have many of the same resources available and produce many of the same products for export as can be seen in the diagrams. However, the availability of the resources and the amount of products produced and/or traded are very different. For example, Venezuela has a greater storage of and dependence on oil while the Colombian economy is more varied.

The emergy analyses show that both countries have a trade imbalance of empower with many of their main partners such as the United States. Odum (1995) stressed the advantage of equal inputs of purchased and renewable resources, in terms of emergy, to a stable economy. In either case, neither Venezuela nor Colombia should be able to maintain stability or long term growth of their economy with an emergy trade deficit. It is commonly believed that neither country's economy has grown significantly in the last 15 years.

The emergy in exports are significant in Venezuela because of the large quantities of oil products sent around the world. The Venezuelan economy suffers an emergy deficit of nearly the same amount of the total emergy used by

the country in the same year. The total amount of emergy exported is actually greater than the total amount of annual emergy used. These indices imply that the Venezuelan economy is exporting resources to other countries and not receiving the real value for those resources in return.

Colombia is in a similar position concerning their import-export economy. However, although they seem to have a higher ratio of emergy per dollar of GDP (sej/US$) than Venezuela, their exchange deficit and total exports to imports ratio is relatively less. Their economy relies on oil, but also on agriculture and steel production. However, tourism and service oriented businesses are less developed in Colombia than in Venezuela.

The infamous illegal drug trade in Colombia and Venezuela were not analyzed because of the difficulty in finding reliable data from inside each country. However, it can be assumed that the illegal drug traffic in Colombia alone may be creating a trade deficit because of the high prices paid for the products. Some agricultural products have higher transformities than even oil. The energy required to hide the illegal fields, drug processing labs, and transport systems may increase the transformities of illegal drugs beyond that of legal crops.

The money received is rarely introduced into the national economy, but rather remains outside the country tied up in foreign investments. Moreover, the money paid for illegal drugs is nearly almost always in US dollars so that losses in emergy may be even greater than in other transactions.

At the regional or state scale, the two systems involved are much more different than at the national scale. The systems diagram of Zulia is very similar to that of Venezuela. Zulia has every ecosystem that can be found in any other part of Venezuela with the exception of the large savannas. Moreover, Lake Maracaibo is located in this state. The resources and products of Zulia are also similar to that of the national economy.

On the other hand, Norte de Santander is predominately tropical forests and agricultural pastures. The ecosystems are primarily those associated with the Catatumbo River drainage basin. The economy has fewer local resources to use and relies mostly on the export of raw materials.

The practice of exporting more emergy than is imported has been carried down to the states, Zulia in Venezuela and Norte de Santander in Colombia, and possibly even to the watershed economy. By trading mostly raw materials in exchange for fuels, goods and services and technology, each region is losing its environmental base to other systems.

Norte de Santander, and hence the Catatumbo drainage basin, is especially vulnerable to negative impacts associated with a trade imbalance. Norte de Santander only adds approximately 3.2% to the Colombian gross national product (Aguirre et al. 1989), but the State is heavily dependent on Colombia for the majority of its goods and services. Hence, even trading with Colombia can cause the state to lose much of its nonrenewable resources that it could use for its own sustainability.

Norte de Santander, Colombia, is also dependent on resources located in the Catatumbo drainage basin. As development grows, purchased inputs will likely increase leading to a similar increase in the use of nonrenewable resources following the predictions of Odum (1995) concering other economies in a similar situation. Development dependent on the export of products with relatively low emergy without at least an equal amount of emergy in exchange will inevitably deteriorate the environmental base.

What is not clear in these emergy analyses is that the two sides of the drainage basin are not in the same stages of development. In that part of Zulia that makes up the Venezuelan side of the drainage basin is actually the most undeveloped area of the State. The side of the drainage basin located in Norte de Santander is much more developed than the downstream Venezuelan side.

Although, the Zulian economy contributes a much higher percentage to their respective national economy, the Catatumbo drainage basin contributions are very minor. Zulia has had long-term interests in the use of resources found in and around Lake Maracaibo. These interests have mainly focused on the abundant oil and coal reserves and the large fishery. Until the state focuses on developing its resources within the State rather than exporting their raw materials, the watershed may be a storage waiting to be similarly exploited.

The potential developed carrying capacity of each country is also not indicative of that of the States. If the resources in Colombia were developed to their maximum potential without decreasing the current living standard, then the population could add approximately 100,000,000 more people, or a growth

increase of 132%. Venezuela under the same circumstances could have a growth increase of 82%, or 62,000,000 people.

At the State level, the Venezuelan State of Zulia could expect a growth increase of 5,000,000 people or an increase of 65% of its present population. Because of the other areas of Zulia that are currently more important to its economy, it is unlikely much of this increase in population would occur in the Catatumbo drainage basin. In contrast, Norte de Santander is closer to its maximum development and expect an increase in only slightly more than 3,000,000 or 40% of its present population. Because over two-thirds of Norte de Santander is the Catatumbo drainage basin, the majority of the new population would settle in the basin.

Spatial Analyses

General differences between the two sides of the drainage basin

The spatial analyses of the Catatumbo River drainage basin show that much of the character of the basin is not apparent in the emergy analyses of the countries and states that share its borders. Although the emergy analyses imply that the two sides of the basin (as divided by the international border) may be different, one may interpret the Venezuelan side to more developed. This is because in Venezuela the average fuel use, import of goods and services, and emergy per person is higher than in Colombia. In fact, it is the Colombian side of the basin that is more developed by agriculture, mining, and population.

Many other contrasting characteristics of the basin are also not revealed by the larger scale emergy analyses including the biogeophysical attributes of the

basin. For example, the Colombian side of the basin has higher elevations and steeper sloped terrain. The majority of the Venezuelan side of the basin is relatively flat and within 200 meters of sea level.

Rain in the basin is quite variable from that considered to be semi-desert conditions (< 600 mm/yr) to that of a rain forest (> 3000 mm/yr). Much of the heavier rain falls in the area along the border between the two countries. In general, the range of different amounts of rainfall occurs in wide bands in a southeastern-northwestern direction. This unique rain pattern is influenced by the converging weather patterns from the Pacific Ocean (via Colombia) and the Caribbean Sea which meet above Lake Maracaibo (Rodriguez, 1973; Pardi, 1979).

The majority of the Venezuelan side of the basin contains soils that are rich in organic matter, but the much of this side also has soils with low fertility. The Colombian side of the Catatumbo drainage basin contains soils containing rich to poor organic matter and low to high fertility. This variety of soils is likely due to a more varied source of soils including mountain erosion which does not occur in the Venezuelan side.

The differences in soil cover, as well as elevation, in the drainage basin are probably largely responsible for the differences in dominant land cover. The Venezuelan side of the basin is largely swamp forest, freshwater marshes, and lowland tropical forest. Much of the Colombian side of the basin that is not too high in elevation or steep of slope is either migrating or permanent agriculture. These fields are used either for crops for raising cattle. The range of land cover

in the Colombian side is uniquely varied from semi-desert to alpine forest and paramo savanas to lowland tropical forest near the Venezuelan border.

The morphological organization of the drainage basin in terms of stream-order watersheds is different also. Colombia contains most of the first to third-order watersheds, while Venezuela contains those of the fourth and fifth-order. The reason for this is that Colombia contains the majority of the headwater streams and the larger tributaries of the basin converge along the border between the two countries.

Empower density

The results of the spatial analyses in terms of emergy reveal other differences between the two sides of the drainage basin. In addition, general longitudinal trends are apparent which follow the river's course and/or stream-order watersheds either upstream or downstream.

Renewable empower density in the form of geo-potential and chemical potential increases downstream. Geologic inputs also increase in a longitudinal pattern but do so in an upstream direction. Such patterns may relate to suggestions by Vannote et al. (1981) that a river system is organized longitudinally. In the case of a watershed, resources transform in a downstream direction into higher, more concentrated forms of available energy. Diamond (1984) proposed the idea of increasing transformity with stream-order due to the transformations of geo-potential energy.

In contrast, development empower concentrates upstream. Odum et al. (1986) suggested that the direction of renewable empower flows and

development flows may be inverse in many watersheds because of the location of resource storages upstream such as groundwater and minerals. It may be that such patterns exist in the Catatumbo drainage basin because of the high emergy storages of rich soils and potential mining materials located in the Colombian watersheds.

As previously mentioned, the average fuel use and import of goods and services between Colombia and Venezuela are different. This could have a significant effect on the distribution of development empower density in the Catatumbo drainage basin. This is why the scaling factor of average income of each county relative to the national average was used. In addition, the population density of the Venezuelan side of the basin is so much lower that even if the scaling factor was not used, the results would likely have been similar.

Almost every stream-order watershed in the basin has some agricultural activity taking place. The highest productivity occurs in the Zulia River watersheds where soils are high in fertility and the slopes are not relatively steep. It is not clear where future increases in agricultural productivity will take place, but it is possible that it will occur where an urban center is close by.

Emergy of storages

The downstream increase of storage of forest biomass, as emergy density, perhaps could have been predicted. There are extensive forests in the Venezuelan side of the drainage basin which make up the downstream stream-order watersheds. In contrast, there are large areas of the Colombian side of the

watershed that are either used for agriculture or are located in higher elevations where forest productivity decreases.

The pattern of emergy density of organic matter in soils is not easy to interpret, but there is a general increase with stream-order watersheds. The highly organic soils of the fifth-order watershed are maintained by the extensive wetlands in those areas including swamp forest and freshwater marshes. The marshes of the Catatumbo drainage basin are the only true lacustrine wetlands in Venezuela, and for this reason much of the fifth-order watershed (2700 km^2) is part of Ciénaga del Catatumbo National Park (Carreño, 1992).

The filteration properties of wetlands has long been studied (for examples see Moshiri, 1993; Hammer, 1989, and Mitsch and Gooselink, 1986). The downstream storages of biomass and soils, in combination with the dilution properties of high discharge, in the Catatumbo drainage basin may buffer the impact of pollutants before the river discharges into Lake Maracaibo.

Overall, the inverse increase of the storages of emergy with stream-order watershed is due to potential mining materials. These storages had to be estimated because surveys of the extent of the various ores are not available. The actual amount of the mining material storages is probably such the results of the analysis would not change significantly. Rather, since the emergy of the mining materials is inherently high because of their emergy per mass, the upper watersheds would still have more stored emergy overall than downstream.

Emergy of water and river constituents

According this study, total nitrogen has higher emergy per volume of river water throughout the drainage basin than total phosphorus. This implies that more total nitrogen is available and may be required to maintain watershed processes. Nevertheless, the emergy per mass of total phosphorus based on its concentration relative to the biosphere is higher than that for total nitrogen. This means that phosphorus could potentially have a greater impact on the ecosystems of the basin. According to the studies of Genoni (1995a; 1995b; 1996) and Genoni and Montague (1997), elements with higher transformities have a greater influence on the productivity of an ecosystem including to the point of being toxic.

The results of Intevep and Ecopetrol (1996) concluded that total nitrogen in the drainage basin has increased over the last ten years. Poorly treated domestic wastes and increases in agriculture, especially in the Zulia River watersheds, are believed to cause the high total nitrogen levels.

The emergy of the constituents per volume of river water increases with the stream-order of the watershed. River sediments strongly influence this pattern because of their high emergy per volume of river water, which also increases with stream-order watershed. Total nitrogen and phosphorus have little influence on total emergy per volume of river water as these constituents are within a relatively narrow range throughout the drainage basin.

Oil spills in the third and fourth-order watersheds elevate the total emergy in those areas. The absence of those spills would be noticeable, especially in

the third-order watershed as it would decrease total emergy of constutients per volume of river water. On the other hand, if the contingency plans were not successfully and consistently carried out, then the emergy of spilled oil per volume of river water [of spilled oil would undoubtedly be much higher since the spills occur on a weekly basis.

The maps of emergy per volume of river water show that with the exception of high total nitrogen, other potential pollutants (total phosphorus, suspended sediment, frequently spilled crude oil) decrease by the time they reach the large floodplains before the water reached Lake Maracaibo. The decrease could be caused by dilution or incorporation into the environment such as plant uptake or sedimentation. Even with the possible storage in the floodplains, the Catatumbo drainage basin still contributes approximately 75% of the nutrients discharged into Lake Maracaibo by its various watersheds.

In the Catatumbo drainage basin, the emergy of river sediment per volume of river watear seems to be high relative to the other constituents. Even though development empower density is lower where soil loss is high, Aguirre et al. (1989) suggests that erosion IS induced by human activity such as poor agricultural practices and lumbering.

During certain times of the year there is an upstream hydrological pressure from Lake Maracaibo into the Catatumbo drainage basin (Pardi, 1979; Rodriguez, 1973). This pressure forces water from the lake into the river floodplains. The hydrologic pressure may elevate nutrient levels and salinity in

the fourth and fifth stream-order watersheds in the Catatumbo drainage basin. The influence of tides and circulation patterns the lake cause this phenomenon.

The general trend common to all the constituents of river water studied is that each has a significant increase in the third-order watershed and has a significant decrease in the fourth-order watershed. The morphology of the river system, rather than any influence of development or other human activity, may be the cause of this pattern. For example, the Zulia tributary is at its terminal a third-order stream, and it contributes more water the main river channel of the Catatumbo than the fourth-order stream to the west. The result is that emergy per volume of river water decreases in the fourth-order watersheds. The significance of this is that development plans must consider the possible greater influence (such as a contributor of energy, nutrients, and materials), in some cases, that the lower-order watersheds have on the downstream system.

The transport ratios of total nitrogen and total phosphorus increase with stream-order watershed. The emergy of these constituents per volume of river water decreases with the stream-order of a watershed while at the same time the geo-potential emergy increases with stream-order watershed. Generally, a decrease in the amount of nutrients is desired or expected by the time river water reaches the downstream system as is the case for the Catatumbo River since Lake Maracaibo is the downstream system. High transport ratios of total nitrogen and total phosphorus may partly indicate the ability of the system to flush those nutrients downstream. In other words, if the transport ratio increases with stream order, then that may mean that the river is successful in reducing water quality.

Hence, steadily increasing geo-potential emergy per solar emjoule of constituent may be necessary to aid the system in the removal of unwanted nutrients.

The transport ratio of river sediments decreases with stream-order watershed. Because sediments often increase downstream and they have a high transformity, then it may not be reasonable to expect an increase in transport ratios of river sediments for most river systems. However, if the emergy of river sediments is increased in the higher-order watersheds, then the transport ratio will decrease even further possibly reflecting a reduction in the efficiency of the river's ability to transport those sediments downstream. Hence, turbidity and sedimentation could occur which could eventually affect the productivity of that watershed and perhaps those downstream from it.

The transport ratio of spilled oil increases downstream although only appearing in the third- and fourth-order watershed. As is the case for total nitrogen and total phosphorus, the increase in available geo-potential emergy may assist in the removal of oil from the system so that it does not reach the floodplains of the Catatumbo River (located in the fifth-order watersheds) nor does the oil affect the fisheries of Lake Maracaibo. Increases in spilled oil may reduce the transport ratio and thereby allow oil to reach farther downstream than it currently does.

Alternative Results Based on Other Watershed Conditions

This section considers what the results of this study might have been if the certtain charateristics of the drainage basin were different. In other words, some of the flows and storages may have been different if the drainage basin had twice

as much or half as much development overall. Other conditions, such as climate, morphology, or size of the drainage basin may have also produced different organizational patterns of the resource flows and/or water quality.

If the drainage basin was less developed, then the renewable flows of empower density would likely be the same. However, the upstream longitudinal trend of development in stream-order watersheds may be either less pronounced or no longer present. Aguirre et al. (1989) studied the settlement history of the Catatumbo drainage basin. As early as 1810 the Colombian side of the basin was already being developed while the Venezuelan side was untouched by the European settlers for more than 100 years later. It is possible then the empower density of development in the early stages of human occupation in the Catatumbo drainage basin would have been similarly organized with respect to stream-order watershed.

The storages of emergy, especially those commercially desirable, in a less developed watershed would likely be different than those of the present day Catatumbo drainage basin. One might argue that the storages of potential mining materials should be considered only if there is interest in extracting the materials. For example, in this study only those materials actually being mined were considered. Various other minerals may exist in the ground below the basin, but without interest in their extraction their emergy value may not affect policy decisions for the placement or extent of development. Under this scenario, the storages of emergy in a less developed basin may increase with stream-order watershed because those storages of biomass and soils could

dominate the emergy density of total storage. The location of potential mining materials could also strongly affect the overall pattern of emergy storage. Oil discoveries or mined peat in the lower watersheds of a basin could make the overall pattern longitudinal, but downstream with stream-order watershed. This the reverse of the situation in the Catatumbo drainage basin.

It is hard to predict what the emergy per volume of river water in a less developed watershed would be because of the many variables governing water quality that are unrelated to development. These would include groundwater inputs to the river, rock face and soil type, erosion rates, sedimentation rates, and exposure to wetlands (Margalef, 1983). However, more development could possibly produce an increase in emergy per volume of river water for nutrients alone if measures to reduce their input were not in place.

Many drainage basins more developed that of the Catatumbo basin include dams used for hydroelectric power, flood control, or the creation of a reservoir. Water may also be diverted in more developed basins for irrigation or use by domestic or industrial purposes. These drainage basins could undoubtedly have a different longitudinal pattern of geo-potential if the retention or diversion of water was larger enough. This would also affect the empower density of the chemical potential of the watersheds which is dependent on the watershed's stream inflow. Certain storages in a more developed drainage basin could be decreased if they were being exploited such as forest biomass or soil fertility.

It is well known that many characteristics of tropical drainage basins are unique compared to those located in other climate zones (Minshall, 1994). If a drainage basin located in colder climate were analyzed using the methods in this study, then downstream pattern of emergy in a volume of river water could be quite different than that of the Catatumbo drainage basin. The biodegradtion or absorbtion of potential of pollutants such as nutrients would be reduced. In cold months, even the dilution of those pollutants may not occur if ice is present. In addition, many drainage basins in colder climates do not have as extensive of floodplains or flooding season as those in the tropics. Hence, the potential for nutrients to be reduced or absorbed over a broader area of plant life is lessened.

The size of a drainage basin may affect the spatial organization of emergy. For example, if the Catatumbo drainage basin was smaller, than its spatial organization may similar to that of a more developed basin as urban areas would be closer together and their needs met in more concentrated areas. Much like the sliding rule corollary to the river-continuum concept (Minshall et al, 1985), the longitudinal patterns of renewable and development empower could be the same as in the Catatumbo basin, just not in the same stream-order watersheds or in the exact same proportion.

The proximity of a drainage basin to large urban centers outside its borders may affect the location and extent of development and use of resources. The geography of an area can determine its long term growth pattern regardless of the location of the most valued resources (Grey, 1994). Hence, if the Catatumbo drainage basin was located such that the Venezuelan side was closer

the capital of Zulia (Maracaibo), then the development of that side of the basin could have been more extensive. Moreover, water quality could have had higher emergy per volume of river water. This scenario may not be ideal especially if the emergy of the river water is high because of untreated domestic and industrial discharges containing heavy metals, high sediment loads, and/or undesirably high loads of nutrients.

If oil spills occurred in Venezuela rather than along the Colombian border, then there would be less time for biodegration of the hydrocarbons to take place and less reaction time for contingency plans to be put into action. However, if the spills occurred in small streams that converge directly with the fifth-order watershed, it may be possible that the dilution properties of the larger tributary could reduce some of the negative impacts that might have otherwise occurred. For example, if the spill took place in the fifth-order watershed, then much of the oil would either contaminate the wetlands or flow directly to the lake. Therefore, not only is proximity to the river's mouth a factor to consider for predicting the impacts of the oil spills, but also in which stream-order watershed did it happen.

Changes in Results Due to Possible Development Plans

Unofficially, it has been discussed at various times that parts of Venezuelan side of the drainage basin could be sold as concessions for oil exploration. If this would happen then the scenario of oil spills occurring closer to Lake Maracaibo and the associated impacts would be envitable. In addition, development in this side of the basin would increase rapidly as the towns grew to accommodate the numerous new residents, albiet possibly temporary, and their

needs for goods and services. Their wastes could enter the stream systems and reach Lake Maracaibo before any remediation, natural or not, could take place. Because of the increased access to the area, other industries might also initiate that are indirectly related the oil exploration such as agriculture, lumbering, and even fishing.

Although no longer presently being considered, in 1990 plans were being discussed to build a train system through the Colombian side of the Catatumbo drainage basin to aid the transport of coal from the mines to processing plants located elsewhere (ICLAM, 1992). The plans were put on hold because it was determined that such a train system would require the removal of a large area of land from agricultural production and cause potential increases in contamination problems of river-water quality. This would mean a possible shift in development empower density which would increase closer to the coal mines and decrease where agricultural productivity was discontinued.

Total development empower density by stream-order watershed would probably increase in the first and second-order watersheds which contain much of the potential mining materials, including coal. Total empower density in the third-order watershed may decrease because much of the agricultural productivity in the drainage basin occurs in the Zulia River watersheds which is a third-order stream.

If the train system provoked increased development upstream, then even renewable sources of empower density may be affected such as geo-potential and chemical potential. Any leveling of steep slopes to allow the train's tracks to

be laid would decrease both. In addition, increases in development would require a consistent water supply. Unless an aquifer is tapped under the basin, the basin's tributaries would mostly likely by the source of that water. According to Aguirre et al. (1989), much of the development in the basin already relies on water from the streams for domestic and industrial uses.

Policy Recommendations

More attention should be focused on smaller scale systems in the watershed to determine if the soil loss is natural erosion or is due to human activity. In addition, development growth in Venezuela should be restricted to maintain the high storages of biomass and soils which may help mitigate potential contamination of Lake Maracaibo. Further growth in the Venezuelan side of the watershed will put more demands on nonrenewable storages as well as aggravate the already over exploited fisheries both in the river and in Lake Maracaibo (Viña and Mojica, 1992).

Growth in the Colombian side of the watershed should increase only at a rate that promotes self-sustainability especially in the form of less trade of raw materials and better agricultural practices. Careful planning should take place that includes predictions on how future development plans might affect the organization of resources in the basin as a whole which would include the Venezuelan side of the watershed.

If improvements are made in controlling the nutrient rich loads suspected of originating from development sources, then the negative impacts the river water might have on Lake Maracaibo are greatly reduced. Hence, any

development in the floodplains may affect this buffering affect on emergy in a volume of river water.

The national parks in both countries are an important investment in the drainage basin and should be maintained and protected from the negative impacts associated with water mediated pollutants. Parks under special protection that include riverine systems and floodplains can fullfill many conservation objectives, such as preserving biodiversity and maintaining biological productivity (Allen and Flecker, 1993). In addition, the presence of the parks may maintain the high storages of biomass and soils that reduce the load of pollutants reaching Lake Maracaibo.

Changes in water quality induced by development may result in substantial changes in floodplain self-organization (Junk et al. 1989). In addition, multiple pollutants from various sources produce more intricate disturbance patterns depending on the pollutant type and intensity (Laws 1993, Haslam 1990). This is an important consideration in the Catatumbo watershed given the economic activities that depend on the floodplain ecosystems. These include fisheries, cattle ranching, and agriculture.

Local and regional economic sectors could eventually be affected if undesirable nutrient loads are continued over a long period. In addition, plans to improve the water quality of Lake Maracaibo should be made a priority as the hydrologic pressure of the lake may be influencing nutrient levels in the watersheds draining into the lake including the Catatumbo drainage basin.

Future Research Recommendations

Effective watershed-management may be accomplished using a scientifically based methodology. This study showed how the influence of development and environmental resources can be understood from many scales of interest. This understanding can aid the chances that future watershed development will have less undesirable impacts on downstream systems.

Scientific inquiry into watershed organization in drainage basins should apply the methods used in this study at the jurisdictional scale of the counties to increase the resolution of the location of development. In addition, involving the urban cities may allow more focus on common goals of development including the reduction of negative impacts to Lake Maracaibo. This should also allow more definitive answers to the validity of the study.

Future areas of research could include the changes in empower density and emergy in a volume of river water if soil management practices were used where human activity is causing high erosion rates. A closer look should also be taken of pesticide use and heavy metals in discharges and their influence on the watershed systems especially emergy in a volume of river water.

Other factors that may direct ecosystem self-organization and the economic components of the system may include land use, habitat loss and degradation from land clearing activities, the introduction of exotic species, and over-exploitation of fisheries. Each of these perturbations can have similar effects as contamination (Allan and Flecker 1993, Laws 1993, Soulé 1991, Miller et al. 1989). This situation may make delineating each pollutant's effect on

emergy in a volume of river water more difficult. Separating out the specific cause and effect of each impact may not be possible nor desirable. Studying the problem from different scales (e.g., local, regional, national, international) using a systems network may alleviate some potential complications.

Research into the impacts of the oil spills should be done on smaller scales that include terrestrial soils, vegetation, and animal life. Moreover, the costs of clean up (equipment, money, damage to ecosystems, etc.) should be evaluated to determine a more accurate depiction of the impacts of oil spills on emergy in a volume of river water. Junk (1989) introduced the flood-pulse concept as a means to understand seasonal changes in a river system and how those changes lead to organizational patterns. It may be instructive to further investigate how seasonal changes in emergy in a volume of river water relate to the flood-pulse concept.

According to Odum (1995, 1986), resources may organize by means of spatial succession. It would be useful to model the flows, storages, and water quality over time, providing enough data can be found to do so, to test this theory for drainage basins. This theory could then add another dimension to effective policy decisions that consider long term options for basin and watershed-management.

It would be interesting to analyze the empower density of renewable resources and development in other watersheds of equal and more or less human activity to see if the inverse longitudinal trends of those flows is a common one. If it is true for the upstream trend of development, then a theory

similar to the river-continuum concept could be tested to see if there is a recognizable development continuum in drainage basins. More studies that determine the organization of energy sources and flows are necessary for comparative research of river systems (Johnson et al., 1995).

The current social atmosphere in the Catatumbo drainage basin was not addressed in this study. For many years, more than fourteen, this basin has been occupied by both illegal drug traffic and guerilla organizations (World Oil, 1996). The frequent oil spills are caused by a specific terrorist group that demand that Colombia nationalize their oil industry as Venezuela once did in the 1970's.

The presence of these groups may affect the rate and extent of development in the basin as few industries desire to have their business where there is the danger of their workers' personal safety outside of their control. How the presence of these groups do actually affect the organization of the watershed would be a useful tool for really trying to solve political tensions between Colombian and Venezuelan in this region. At the time of this study, information concerning these groups was either unavailable or not for public distribution.

APPENDIX A
GLOSSARY

Areal weighted average-an average of the spatial distribution of something spread over an area that has multiple sectors. The total of the quantity in each sector is multiplied by a ratio of the area of the sector in which it is located to the area of the over which the average is desired. The result of each individual sector is then added together to determine the areal average of the larger area.

Attribute-a quantitative or qualitative value assigned to a given point, line or polygon.

Base map – a map showing planimetric, topographic, geologic, political, and/or cadastral (value, ownership, extent of land as basis for taxation) information that may appear in many different types of maps. The base map information is drawn with other types of thematic information that may be used to construct other coverages based on that original information.

Constituent of river water-an element or substance that makes up part of the solid materials in the river water column.

Coverage-a GIS map.

Development-activity related to the human occupation of an area. Development can be represented by different attributes such as physical (housing, buildings), zonal (respresentative of the type of activity taking place such as residential, industrial, passive parks), numerical (population density), or road network.

Drainage basin-the area that has a network of streams converging in a common direction towards a common outlet such as the mouth of a river.

Emdollar-formerly known as the macroeconomic dollar, the emdollar is a measure of a country's emergy flow (used) to its gross domestic product. The units of the emdollar are solar emjoules per US dollar or sej/US$.

Emergy-a science based evaluation measure that represents both the environmental values and economic values. Emergy measures both the work of nature and that of humans in generating products and services. The units of emergy are measured in solar emjoules or sej.

Emergy per mass-the emergy required to produce a certain weight of something. The units are generally solar emjoules per gram or sej/g.

Emergy volume-the emergy required to produce a volume of something. In this study, the volume is that of a river's discharge. Hence, the units of emergy volume is solar emjoules per cubic meter of river water or sej/m^3.

Empower-the flow of emergy over time. The units of empower are usually solar emjoules per year or sej/yr.

Goods-miscellaneous products bought or sold in an economy.

Polygon- a raster based (a GIS system that uses an imaginary grid of cells) delineation of an area that is composed of a set of contiguous cells defining the interior.

Renewable-something that is continually replaced so that a flow from its source will not diminish in the foreseeable future.

Sector-a section of a coverage delineated for convenience of referencing.

Segment-that part of a tributary that is between junctions of other tributaries.

Services-miscellaneous activities in an economy that are performed for the exchange of money. Generally, services do not include the making of products.

Stream order-a number representative of the position in a river's network or hierarchy of its many tributaries. First order streams are those tributaries that form the beginning or headwaters of the river. As the tributaries of the same stream order converge, the stream order of the resultant tributary increases by one.

Thematic map-a map that illustrates a single subject or topic either quantitatively or qualitatively.

Transformity-a conversion measure that is used to represent the amount of solar emjoules in one joule of something, sej/j.

Watershed-sub-basin. an area that drains into a tributary of a larger river. All the watersheds of a river's tributaries together form the river's drainage basin.

APPENDIX B
ENERGY CONTENT, TRANSFORMITY, and EMERGY PER MASS

Energy Content

In order to calculate emergy, it is often necessary to know the energy content of a particular material. The energy content is then multiplied by the quantity or density of the material to determine its energetic potential. In some cases, it may be necessary to account for certain forces acting on the material, such as gravity, instead of using energy content to determine the energetic potential. The energy content required of items analyzed in this work was taken from Table B-1. These measures were all previously determined from other studies.

Transformity and Emergy per Mass

Also in Table B-1 are the predetermined transformities and emergy per mass used in this study. These conversion measures were multiplied by either the energy content of a material or its total weight to determine the emergy required for its existence.

The emergy per mass of nitrogen, phosphorus, and river sediments in river water was determined using methods suggested by Dr. Mark Brown (*personal communication, June 23, 1998. University of Florida, Gainesville, Florida*) and the works of Brandt (1998), Foley (1998), and Odum et al. (1998).

Table B-1. List of transformities and energy content measurements taken from the literature and used in this study.

	Item	Energy Content	Units	Ref.	Trans-formity	Units	Ref.
1	Solar insolation				1	sej/J	*a*
2	Wind				6.23E+02	"	*a*
3	Earth cycle				6.06E+03	"	*a*
4	Rain physical energy				1.05E+04	"	*a*
5	Stream chemical potential*	1E3	g/km^2	*b*	1.11E+04	"	*c*
6	Rain chemical potential	1E3	g/km^2	*b*	1.82E+04	"	*b*
7	Forest extraction				1.87E+04	"	*b*
8	Tide				2.36E+04	"	*a*
9	Waves				2.59E+04	"	*a*
10	Stream physical energy				2.78E+04	"	*a*
11	Coal	3.18E10	J/ton	*a*	4.00E+04	"	*b*
12	Natural gas	1.056E3	J/BTU	*a*	4.80E+04	"	*a*
13	Crude oil	6.28E9	J/bbl	*a*	5.40E+04	"	*b*
14	Sediments in river	5.4	Cal/g	*a*	6.30E+04	"	*c*
15	Pesticides				6.60E+04	"	*d*
16	Oil dervided products				6.60E+04	"	*a*
17	Plastics and rubber	9.40E6	J/kg	*c*	6.6E+04	"	*a*
18	Electricity	3.60E6	J/kwh	*a*	1.59E+05	"	*a*
19	Agricultural production	5E3	J/kg	*a*	2.00E+05	"	*b*
20	Livestock	4E3	J/kg	*c*	2.00E+05	"	*b*
21	Fisheries	4E3	J/kg	*c*	2.00E+05	"	*b*
22	Wood, paper, etc.				1.30E+06	"	*a*
23	Nitrogen	2.17E9	J/g	*a*	1.69E+06	"	*c*
24	Phosphorus	348	J/g	*a*	4.14E+07	"	*c*
25	Iron ore	14.2	J/g	*a*	6.01E+07	"	*a*
26	Mechanical&transportation equipment				6.70E+09	sej/g	*a*
27	Chemicals				3.80E+08	"	*a*
28	Clay				2.00E+09	"	*a*
29	Crude steel				2.64E+09	"	*a*
30	Steel				2.64E+09	"	*a*

**Gibbs Free energy for stream chemical potential was calculated using water quality data taken from monitoring stations located along the river. See text for more details.*

a Odum (1996)

b Brown and Arding (1991)

c Brown and McClanahan (1992)

d Odum (1994) (17.1% of country production)

APPENDIX C
ENERGY CALCULATIONS FOR EMERGY ANALYSIS

Table C-1. Footnotes to Table 4.

1 SOLAR ENERGY

Cont. Shelf Area	=	8.34E+10 m^2	(UN 1992)
Land Area	=	9.12E+11 m^2	(UN 1992)
Insolation	=	4.14E+02 kcal/cm^2/y	(Veillon 1989)
Albedo	=	0.30 (% given as decimal)	(Veillon 1989)

Energy (J) = (area incl shelf)*(avg insolation)*(1-albedo)
= (_m^2)*(_kcal/cm^2/y)*
(1e4cm^2/m^2)*(1-0.03)*(4186J/kcal)
= 1.21E+21

2 EARTH CYCLE

Land Area	=	9.12E+11 m^2	
Heat flow per area	=	1.00E+06 J/m^2/y	(Veillon 1989)

Energy (J) = (area)*(heat flow per area)
= (_m^2)*(_J/m^2/y)
= 9.12E+17

3 RAIN, CHEMICAL POTENTIAL ENERGY

Cont. Shelf Area	=	8.34E+10 m^2	
Land Area	=	9.12E+11 m^2	
Rain (shelf)	=	0.75 m/yr	(Veillon 1989)
Rain (land)	=	2.75 m/yr	(Veillon 1989)
Evapotrans rate	=	0.70	(Veillon 1989)

Energy (shelf) (J) = (area)*(rainfall)*(Gibbs no.)
= (_m^2)*(_m/y)*(1000 kg/m^3)*(4940 J/kg)
= 3.09E+17

Table C-1. --continued.

8 RIVER GEOPOTENTIAL

Flow	=	3.60E+04 m^3/s	(Hernadez 1987)
Elevation change	=	5.00E+02 m	(Hernadez 1987)
Energy (J)	=	(flow)*(elevation change)*(gravity)*(seconds/year)*(water weight)	
	=	(_m^3)*(_m)*(9.8m/s^2)*(3.1E7s/y)*(1000kg/m^3)*(0.5)	
Total	=	5.56E+18	

9 AGRICULTURAL PRODUCTION

Production	=	3.95E+10 Tons	(UN 1992)
Energy (J)			
	=	(_ tons)*(2205 lbs/ton)*(453.6 g/lb)*(4.5 kcal/g)*(4186 J/kcal)	
	=	1.78E+17	

10 ELECTRICITY

Consumption	=	5.80E+10 Kwh	(CIA 1994)
Energy (J)			
	=	(_Kwh)*(3.60E6J/kwh)	
	=	2.09E+17	

11 LIVESTOCK PRODUCTION

Average weight	=	6.20E+09 lbs	(UN 1992)
Energy (J)			
	=	(_heads)*(_lb)*(453.6 g/lb)*(4 kcal/g)*(4186J/g)	
	=	4.71E+16	

12 FISHING PRODUCTION

Fish Catch	=	3.32E+05 MT	(UN 1992)
Energy (J)			
	=	(_MT)*(1E6g/MT)*(4kcal/g)*(4186J/kcal)	
	=	5.56E+15	

13 FOREST EXTRACTION

Harvest	=	3.25E+05 m^3	(UN 1992)
Energy (J)			
	=	(_ m^3)*(0.5E6 g/m^3)*(3.6kcal/g)*(4186J/kcal)	
	=	2.45E+15	

Table C-1. --continued.

14 NATURAL GAS			
Consumption	=	2.71E+13 m^3	(UN 1992)
Energy (J)			
	=	(_m^3)/(1m^3/35.32ft^3)(1.1e6J/ft^3)	
	=	8.45E+17	
15 CRUDE OIL			
Consumption	=	1.02E+08 bbls	(UN 1992)
Energy (J)			
	=	(_bbls)*(42gal/bbl)*(3.8 l/gal)*(9800 Cal/l*(4186J/Cal)	
	=	6.68E+17	
16 FERTILIZERS			
Production	=	3.93E+11 grams	(UN 1992)
17 MINERALS (gold, silver, lead, aluminum, tin)			
Production	=	9.18E+12 grams	(UN 1992)
18 CRUDE STEEL			
Production	=	3.14E+09 grams	(UN 1992)
19 IRON ORE			
Production	=	1.3034E+13 grams	(UN 1992)
Energy (J)			
	=	(_grams)*(14.2 J/g)	
	=	1.8508E+14	
20 OIL DERIVED PRODUCTS			
Imports	=	7.88E+07 BBL	(UN 1992)
Energy (J)			
	=	(_BBL)*(6.28E9 J/BBL)	
	=	4.95E+17	
21 STEEL			
Imports	=	8.80E+11 g	(UN 1992)
22 MINERALS	=	5.11E+12 g	(UN 1992)

Table C-1. --continued.

23 AGRICULTURAL AND FORESTRY PRODUCTS				
Imports	=	4.07E+06 m^3		(UN 1992)
Energy (J)				
	=	(_ m^3)*(0.5E6 g/m^3)*(3.6kcal/g)*(4186J/kcal)		
	=	3.07E+16		
24 LIVESTOCK				
Imports	=	1.47E+08 avg. total weight		(UN 1992)
Energy (J)				
	=	(_lb)*(453.6 g/lb)*(4 kcal/g)*(4186J/g)		
	=	1.12E+15		
25 FOODS				
Imports	=	1.08E+06 m^3		(UN 1992)
Energy (J)				
	=	(_ m^3)*(0.5E6 g/m^3)*(3.6kcal/g)*(4186J/kcal)		
	=	8.12E+15		
26 PLASTICS & RUBBER				
Imports	=	1.53E+08 kg		(UN 1992)
Energy (J)				
	=	(_kg)(9.4E6J/kg)		
	=	1.44E+15		
27 CHEMICALS				
Imports	=	1.59E+12	g	(UN 1992)
28 WOOD, PAPER, ETC.				
Imports	=	5.70E+05 MT		(UN 1992)
Energy (J)				
	=	(_MT)*(1E6 g/MT)*(15E3 J/g)		
	=	8.55E+15		
29 MECHANICAL & TRANSPORATION EQUIPMENT				
Imports	=	4.41E+11	g	(UN 1992)
30 SERVICES				
	=	1.10E+10	$	(UN 1992)
31 TOURISM				
	=	2.29E+09	$	(UN 1992)

Table C-1. --continued.

32 CASH CROPS				
Exports	=	2.53E+05 m^3		(UN 1992)
Energy (J)				
	=	(_ m3)*(0.5E6 g/m3)*(3.6kcal/g)*(4186J/kcal)		
	=	1.91E+15		
33 FISHERY PRODUCTS				
Exports	=	7.70E+04 MT		(UN 1992)
Energy (J)				
	=	(_MT)*(1E6g/MT)*(4kcal/g)*(4186J/kcal)		
	=	1.29E+15		
34 LIVESTOCK				
Exports	=	2.57E+07 avg. total weight		(UN 1992)
Energy (J)				
	=	(_lb)*(453.6 g/lb)*(4 kcal/g)*(4186J/g)		
	=	1.95E+14		
35 OIL DERIVED PRODUCTS				
Exports	=	6.59E+08 BBL		(UN 1992)
Energy (J)				
	=	(_BBL)*(6.28E9 J/BBL)		
	=	4.14E+18		
36 STEEL				
Exports	=	1.80E+13	g	(UN 1992)
37 MINERALS				
Exports	=	7.10E+12	g	(UN 1992)
38 CHEMICAL				
Exports	=	8.39E+11	g	(UN 1992)
39 SERVICES IN EXPORTS				
	=	1.42E+10	$	(UN 1992)
40 TOURIST SERVICE				
	=	2.00E+08	$	(UN 1992)

Table C-2. Footnotes to Table 6.

1 SOLAR ENERGY

Cont. Shelf Area	=	1.00E+11 m^2	(IGAC 1992)
Land Area	=	1.04E+12 m^2	(IGAC 1992)
Insolation	=	3.50E+02 $kcal/cm^2/y$	(IGAC 1992)
Albedo	=	0.30 (% given as decimal)	

Energy (J) = (area incl shelf)*(avg insolation)*(1-albedo)
= (_m^2)*(_$kcal/cm^2/y$)*
($1e4 cm^2/m^2$)*(1-0.03)*(4186J/kcal)
= 1.17E+21

2 EARTH CYCLE

Land Area	=	1.04E+12 m^2	
Heat flow per area	=	1.00E+06 $J/m^2/y$	(IGAC 1992)

Energy (J) = (area)*(heat flow per area)
= (_m^2)*(_$J/m^2/y$)
= 1.04E+18

3 RAIN, CHEMICAL POTENTIAL ENERGY

Cont. Shelf Area	=	1.00E+11 m^2	
Land Area	=	1.04E+12 m^2	
Rain (shelf)	=	0.75 m/yr	(IGAC 1992)
Rain (land)	=	2.75 m/yr	(IGAC 1992)
Evapotrans rate	=	0.60	(IGAC 1992)

Energy (shelf) (J) = (area)*(rainfall)*(Gibbs no.)
= (_m^2)*(_m/y)*(1000 kg/m^3)*(4940 J/kg)
= 3.71E+17

Energy (land) (J) = (area)*(evapotrans)*(rainfall)*(Gibbs no.)
= (_m^2)*(_%)*(_m/y)*(1000 kg/m^3)*
(4940 J/kg)
= 8.47E+18

Energy (J = 8.84E+18

4 RAIN, GEOPOTENTIAL ENERGY

Area	=	1.04E+12 m^2
Rainfall (land)	=	2.75 m/yr
Avg Elevation	=	500 m
Runoff rate	=	0.40 (1.0-ET)

Table C-2. --continued.

Energy (J)	=	(area)*(%runoff)*(rainfall)*(avg elevation)*(gravity)
	=	(_m^2)*(_%)*(_m/y)*(1000 kg/m^3)*(_m)* (9.8m/s^2)
	=	5.60E+18

5 WIND ENERGY

Energy (J)	=	2.90E+18 (IGAC 199

6 TIDAL ENERGY

Cont. Shelf Area	=	1.00E+11 m^2	
Avg Tide Range	=	1.00 m	(IGAC 1992)
Density	=	1.03E+03 kg/m^3	(IGAC 1992)
Tides/yr	=	365	(IGAC 1992)

Energy (J)	=	(shelf)*(mean tidal range)^2*(tides/y)* (0.50 energy absorbed)*(density of seawater)* (gravity)
	=	(_m^2)*(_m)*(tides/y)*(_ kg/m^3)*(%)* (9.8m/s^2)
	=	3.67E+17

7 WAVE ENERGY

Shoreline	=	2.50E+06 m	
avg height	=	1.00 m	(IGAC 1992)

Energy (J)	=	(shoreline)*(1/8)*(avg height)^2*(velocity)* (density of seawater)*(gravity)
	=	(_m)*(1/8)*(_m)^2*(9.8m/s^{2}xavg hieght)$^{1/2}$* (1025kg/m^3)*(9.8m/s^2)*(3.154E7 s/y)
	=	3.10E+17

8 RIVER GEOPOTENTIAL

Flow	=	1.00E+04 m^3/s	(IGAC 1992)
Elevation change	=	5.00E+02 m	

Energy (J)	=	(flow)*(elevation change)*(gravity)*(seconds/year)* (water weight)
	=	(_m^3)*(_m)*(9.8m/s^2)*(3.1E7s/y)* (1000kg/m^3)*(0.5)
Total	=	1.54E+18

9 AGRICULTURAL PRODUCTION

Production	=	1.16E+07 Tons	(UN 1992)

Table C-2. --continued.

Energy (J)			
	=	(_ tons)*(2205 lbs/ton)*(453.6 g/lb)*(4.5 kcal/g)*(4186 J/kcal)	
	=	2.18E+17	
10 ELECTRICITY			
Consumption	=	3.46E+10 Kwh	(UN 1992)
Energy (J)			
	=	(_Kwh)*(3.60E6J/kwh)	
	=	1.247E+17	
11 LIVESTOCK PRODUCTION			
Bovines	=	2.49E+07 heads	(UN 1992)
Average weight	=	5.00E+02 lbs	
Pigs	=	2.70E+06 heads	(UN 1992)
Average weight	=	5.00E+02 lbs	
Horses, sheep, mules		6.05E+06 heads	(UN 1992)
Average weight	=	3.00E+02 lbs	
Energy (J)			
	=	(_heads)*(_lb)*(453.6 g/lb)*(4 kcal/g)*(4186J/g)	
	=	1.38E+16	
12 FISHING PRODUCTION			
Fish Catch	=	1.01E+05 MT	(UN 1992)
Energy (J)			
	=	(_MT)*(1E+06g/MT)*(4kcal/g)*(4186J/kcal)	
	=	1.69E+15	
13 FOREST EXTRACTION			
Harvest	=	7.21E+05 m^3	(UN 1992)
Energy (J)			
	=	(_ m^3)*(0.5E+06 g/m^3)*(3.6kcal/g)*(4186J/kcal)	
	=	5.43E+15	
14 NATURAL GAS			
Consumption	=	8.20E+13 BTU	(UN 1992)
Energy (J)			
	=	(_BTU)*(1055.056J/BTU)	
	=	8.65E+16	
15 CRUDE OIL			
Consumption	=	4.08E+14 BTU	(UN 1992)

Table C-2. --continued.

Energy (J)				
	=	(_BTU)*(1055.056J/BTU)		
	=	4.30E+17		
16 FERTILIZERS				
Production	=	4.387E+11	grams	(UN 1992)
17 MINERALS (gold, silver, lead, aluminum, tin)				
Production	=	7.03E+09	grams	(UN 1992)
18 CRUDE STEEL				
Production	=	7.33E+11	grams	(UN 1992)
19 IRON ORE				
Production	=	2.61E+11	grams	(UN 1992)
Energy (J)				
	=	(_grams)*(14.2 J/g)		
	=	3.706E+12		
20 OIL DERIVED PRODUCTS				
Imports	=	1.20E+08	BBL	(UN 1992)
Energy (J)				
	=	(_BBL)*(6.28E9 J/BBL)		
	=	7.55E+17		
21 STEEL				
Imports	=	1.01E+11	g	(UN 1992)
22 MINERALS	=	1.12E+12	g	(UN 1992)
23 AGRICULTURAL AND FORESTRY PRODUCTS				
Imports	=	7.09E+05	m^3	(UN 1992)
Energy (J)				
	=	(_ m^3)*(0.5E+06 g/m^3)*(3.6kcal/g)*(4186J/kcal)		
	=	5.34E+15		
24 LIVESTOCK				
Imports	=	1.18E+08	avg. total weight	(UN 1992)
Energy (J)				

Table C-2. --continued.

	=	(_lb)*(453.6 g/lb)*(4 kcal/g)*(4186J/g)		
	=	9.00E+14		
25 FOODS				
Imports	=	9.29E+05 m^3		(UN 1992)
Energy (J)				
	=	(_ m^3)*(0.5E+06 g/m^3)*(3.6kcal/g)*(4186J/kcal)		
	=	7.00E+15		
26 PLASTICS & RUBBER				
Imports	=	2.46E+08 kg		(UN 1992)
Energy (J)				
	=	(_kg)(9.4e6J/kg)		
	=	2.31E+15		
27 CHEMICALS				
Imports	=	1.59E+12	g	(UN 1992)
28 WOOD, PAPER, ETC.				
Imports	=	6.67E+05 MT		(UN 1992)
Energy (J)				
	=	(_MT)*(1E6 g/MT)*(15E3 J/g)		
	=	1.00E+16		
29 MECHANICAL & TRANSPORATION EQUIPMENT				
Imports	=	3.43E+11	g	(UN 1992)
30 SERVICES				
	=	9.87E+09	$	(UN 1992)
31 TOURISM				
	=	7.45E+09	$	(UN 1992)
32 CASH CROPS				
Exports	=	4.55E+05 m^3		(UN 1992)
Energy (J)				
	=	(_ m^3)*(0.5E+06 g/m^3)*(3.6kcal/g)*(4186J/kcal)		
	=	3.43E+15		
33 FISHERY PRODUCTS				
Exports	=	5.38E+04 MT		(UN 1992)
Energy (J)				
	=	(_MT)*(1E+06g/MT)*(4kcal/g)*(4186J/kcal)		
	=	9.00E+14		(UN 1992)

Table C-2. --continued.

34 LIVESTOCK				
Exports	=	4.25E+07 avg. total weight		
Energy (J)				
	=	(_lb)*(453.6 g/lb)*(4 kcal/g)*(4186J/g)		
	=	3.23E+14		
35 OIL DERIVED PRODUCTS				
Imports	=	3.36E+08 BBL		(UN 1992)
Energy (J)				
	=	(_BBL)*(6.28E9 J/BBL)		
	=	2.11E+18		
36 STEEL				
	=	8.45E+12	g	(UN 1992)
37 MINERAl				
Imports	=	1.78E+13	g	(UN 1992)
38 CHEMICALS				
Imports	=	1.07E+12	g	(UN 1992)
39 SERVICES IN EXPORTS				
	=	2.63E+09	$	(UN 1992)
40 TOURIST SERVICE				
	=	5.15E+08	$	(UN 1992)

Table C-3. Footnotes for Table 8. (unless otherwise noted, all data come from MARAVEN 1987).

1 SOLAR ENERGY

Lake Maracaibo Area	=	1.20E+10 m^2	
Land Area	=	5.02E+10 m^2	
Insolation	=	4.40E+02 kcal/cm^2/y	
Albedo	=	3.00E-01 (% given as decimal)	
Energy (J)	=	(area incl shelf)*(avg insolation)*(1-albedo)	
	=	(_m^2)*(_kcal/cm^2/y)* (1E4cm2/m2)*(1-0.03)*(4186J/kcal)	
	=	8.02E+19	

2 EARTH CYCLE

Land Area	=	5.02E+10 m^2	
Heat flow per area	=	1.00E+06 J/m^2/y	
Energy (J)	=	(area)*(heat flow per area)	
	=	(_m^2)*(_J/m^2/y)	
	=	5.02E+16	

3 RAIN, CHEMICAL POTENTIAL ENERGY

Lake Maracaibo Area	=	1.20E+10 m^2	(Pardi 1989)
Land Area	=	5.02E+10 m^2	
Rain (lake)	=	5.27E-01 m/yr	(Pardi 1989)
Rain (land)	=	1.50E+00 m/yr	(Pardi 1989)
Evapotrans rate	=	7.00E-01	(Pardi 1989)
Energy (shelf) (J)	=	(area)*(rainfall)*(Gibbs no.)	
	=	(_m^2)*(_m/y)*(1000 kg/m^3)*(4940 J/kg)	
	=	3.13E+16	
Energy (land) (J)	=	(area)*(evapotrans)*(rainfall)*(Gibbs no.)	
	=	(_m^2)*(_%)*(_m/y)*(1000 kg/m^3)* (4940 J/kg)	
	=	2.61E+17	
Energy (J)	=	2.92E+17	

4 RAIN, GEOPOTENTIAL ENERGY

Area	=	5.02E+10 m^2	
Rainfall (land)	=	1.50E+00 m/yr	
Avg Elevation	=	3.75E+02 m	
Runoff rate	=	3.00E-01 (1.0-ET)	

Table C-3. --continued.

Energy (J)	=	(area)*(%runoff)*(rainfall)*(avg elevation)*(gravity)	
	=	(_m^2)*(_%)*(_m/y)*(1000 kg/m^3)*(_m)* (9.8m/s^2)	
	=	8.31E+16	
5 WIND ENERGY			
Energy (J)	=	2.90E+18 (Pardi 1989)	
6 TIDAL ENERGY			
Lake Maracaibo Area	=	1.20E+10 m^2	(Pardi 1989)
Avg Tide Range	=	3.30E-01 m	(Pardi 1989)
Density	=	1.03E+03 kg/m^3	(Pardi 1989)
Tides/yr	=	3.65E+02	(Pardi 1989)
Energy (J)	=	(shelf)*(mean tidal range)^2*(tides/y)* (0.50 energy absorbed)*(density of seawater)* (gravity)	
	=	(_m^2)*(_m)*(tides/y)*(_ kg/m^3)*(%)* (9.8m/s^2)	
	=	4.80E+15	
7 WAVE ENERGY			
Shoreline	=	5.70E+02 m	(Pardi 1989)
avg height	=	5.00E-01 m	(Pardi 1989)
Energy (J)	=	(shoreline)*(1/8)*(avg height)^2*(velocity)* (density of seawater)*(gravity)	
	=	(_m)*(1/8)*(_m)2*(9.8m/s^{2}xavg height)$^{1/2}$* (1025kg/m^3)*(9.8m/s^2)*(3.154E7 s/y)	
	=	1.25E+13	
8 RIVER GEOPOTENTIAL			
Flow	=	1.60E+04 m^3/s	(Pardi 1989)
Elevation change	=	5.00E+02 m	(Pardi 1989)
Energy (J)	=	(flow)*(elevation change)*(gravity)*(seconds/year)* (water weight)	
	=	(_m^3)*(_m)*(9.8m/s^2)*(3.1E7s/y)* (1000kg/m^3)*(0.5)	
Total	=	2.47E+18	
9 AGRICULTURAL PRODUCTION			
Production	=	6.75E+09 Tons (17.1% of country production)	

Table C-3. --conintued.

Energy (J)		
	=	(_ tons)*(2205 lbs/ton)*(453.6 g/lb)*(4.5 kcal/g)*(4186 J/kcal)
	=	3.04E+16
10 ELECTRICITY		
Consumption	=	3.82E+09 Kwh
Energy (J)		
	=	(_Kwh)*(3.60E6J/kwh)
	=	1.37E+16
11 LIVESTOCK PRODUCTION		
Average weight	=	1.69E+08 liters milk
Energy (J)		
	=	(_liters)*(4 kcal/g)*(4186J/g)
	=	2.83E+12
12 FISHING PRODUCTION		
Fish Catch	=	1.99E+05 MT
Energy (J)		
	=	(_MT)*(1E6g/MT)*(4kcal/g)*(4186J/kcal)
	=	3.34E+15
13 FOREST EXTRACTION		
Harvest	=	2.99E+04 m^3
Energy (J)		
	=	(_ m3)*(0.5E6 g/m3)*(3.6kcal/g)*(4186J/kcal)
	=	2.25E+14
14 NATURAL GAS		
Consumption	=	1.21E+11 m^3
Energy (J)		
	=	(_m3)/(1m3/35.32ft3)(1.1E6J/ft3)
	=	3.78E+15
15 CRUDE OIL		
Consumption	=	1.47E+07 bbls
Energy (J)		
	=	(_bbls)*(42gal/bbl)*(3.8 l/gal)*(9800 Cal/l*(4186J/Cal)
	=	9.62E+16
16 MINERALS (gold, silver, lead, aluminum, tin)		
Production	=	8.75E+11 grams
17 OIL DERIVED PRODUCTS		
Imports	=	2.36E+07 BBL

Table C-3. --continued.

Energy (J)		
	=	(_BBL)*(6.28E9 J/BBL)
	=	1.48E+17
18 STEEL		
Imports	=	2.64E+11 g
19 MINERALS		
Imports	=	1.53E+12 g
20 AGRICULTURAL AND FORESTRY PRODUCTS		
Imports	=	1.22E+06 m^3
Energy (J)		
	=	(_ m3)*(0.5E6 g/m3)*(3.6kcal/g)*(4186J/kcal)
	=	9.20E+15
21 LIVESTOCK		
Imports	=	4.41E+07 avg. total weight
Energy (J)		
	=	(_lb)*(453.6 g/lb)*(4 kcal/g)*(4186J/g)
	=	3.35E+14
22 FOODS		
Imports	=	3.24E+05 m^3
Energy (J)		
	=	(_ m3)*(0.5E6 g/m3)*(3.6kcal/g)*(4186J/kcal)
	=	2.44E+15
23 PLASTICS & RUBBER		
Imports	=	4.59E+07 kg
Energy (J)		
	=	(_kg)(9.4E6J/kg)
	=	4.31E+14
24 CHEMICALS		
Imports	=	4.77E+11 g
25 WOOD, PAPER, ETC.		
Imports	=	1.71E+05 MT
Energy (J)		
	=	(_MT)*(1E6 g/MT)*(15E3 J/g)
	=	2.57E+15
26 MECHANICAL & TRANSPORATION EQUIPMENT		
Imports	=	1.32E+11 g

Table C-3. --continued.

27 SERVICES
= 3.30E+09 $

28 TOURISM
= 2.29E+08 $

29 CASH CROPS
Exports = 1.77E+05 m^3
Energy (J)
= (_ m3)*(0.5E6 g/m3)*(3.6kcal/g)*(4186J/kcal)
= 1.91E+15

30 FISHERY PRODUCTS
Exports = 5.39E+04 MT
Energy (J)
= (_MT)*(1E6g/MT)*(4kcal/g)*(4186J/kcal)
= 9.03E+14

31 LIVESTOCK
Exports = 1.80E+07 avg. total weight
Energy (J)
= (_lb)*(453.6 g/lb)*(4 kcal/g)*(4186J/g)
= 1.37E+14

32 OIL DERIVED PRODUCTS
Exports = 4.82E+08 BBL
Energy (J)
= (_BBL)*(6.28E9 J/BBL)
= 3.03E+18

33 MINERALS
Exports = 4.97E+12 g

34 CHEMICALS
Exports = 5.87E+11 g

35 SERVICES IN EXPORTS
= 9.94E+09 $

36 TOURIST SERVICE
= 2.00E+07 $

Table C-4. Footnotes to Table 10. (unless other wise noted, all data come from Aguirre et al. (1989)

1 SOLAR ENERGY

Land Area	=	2.72E+10 m^2	
Insolation	=	4.40E+02 $kcal/cm^2/y$	(Veillon 1989)
Albedo	=	3.00E-01 (% given as decimal)	
Energy (J)	=	(area incl shelf)*(avg insolation)*(1-albedo)	
	=	(_m^2)*(_$kcal/cm^2/y$)* (1e4cm^2/m^2)*(1-0.03)*(4186J/kcal)	
	=	3.51E+19	

2 EARTH CYCLE

Land Area	=	2.72E+10 m^2
Heat flow per area	=	1.00E+06 $J/m^2/y$
Energy (J)	=	(area)*(heat flow per area)
	=	(_m^2)*(_$J/m^2/y$)
	=	2.72E+16

3 RAIN, CHEMICAL POTENTIAL ENERGY

Land Area	=	2.72E+10 m^2	
Rain (land)	=	1.50E+00 m/yr	
Evapotrans rate	=	7.00E-01	(Pardi 1989)
Energy (J)	=	(area)*(rainfall)*(Gibbs no.)	
	=	(_m^2)*(_m/y)*(1000 kg/m^3)*(4940 J/kg)	
	=	1.41E+17	

4 RAIN, GEOPOTENTIAL ENERGY

Area	=	2.72E+10 m^2
Rainfall (land)	=	1.50E+00 m/yr
Avg Elevation	=	5.00E+02 m
Runoff rate	=	3.00E-01 (1.0-ET)
Energy (J)	=	(area)*(%runoff)*(rainfall)*(avg elevation)*(gravity)
	=	(_m^2)*(_%)*(_m/y)*(1000 kg/m^3)*(_m)* (9.8m/s^2)
	=	6.00E+16

5 WIND ENERGY

Energy (J)	=	2.90E+18

6 RIVER GEOPOTENTIAL

Flow	=	4.95E+02 m^3/s
Elevation change	=	5.00E+01 m

Table C-4. --continued.

Energy (J) = (flow)*(elevation change)*(gravity)*(seconds/year)*(water weight)
= (_m^3)*(_m)*(9.8m/s^2)*(3.1E7s/y)*(1000kg/m^3)*(0.5)

Total = 7.64E+15

7 AGRICULTURAL PRODUCTION

Production = 2.47E+05 Tons

Energy (J)
= (_ tons)*(2205 lbs/ton)*(453.6 g/lb)*(4.5 kcal/g)*(4186 J/kcal)
= 4.65E+15

8 ELECTRICITY

Consumption = 1.74E+05 Kwh

Energy (J)
= (_Kwh)*(3.60E6J/kwh)
= 6.25E+11

9 NATURAL GAS

Consumption = 8.20E+13 BTU

Energy (J)
= (_BTU)*(1055.056J/BTU)
= 8.20E+11

10 CRUDE OIL

Consumption = 7.68E+16 BTU

Energy (J)
= (_BTU)*(1055.056J/BTU)
= 4.30E+15

11 FERTILIZERS

Production = 4.39E+09 grams

12 MINERALS (gold, silver, lead, aluminum, tin)

Production = 7.03E+09 grams

13 IRON ORE

Production = 2.61E+11 grams

Energy (J)
= (_grams)*(14.2 J/g)
= 3.71E+12

14 OIL DERIVED PRODUCTS

Imports = 1.20E+08 BBL

Table C-4. --continued.

Energy (J)

= (_BBL)*(6.28E9 J/BBL)

= 7.55E+15

15 AGRICULTURAL AND FORESTRY PRODUCTS

Imports = 7.09E+05 m^3

Energy (J)

= (_ m^3)*(0.5E+06 g/m^3)*(3.6kcal/g)*(4186J/kcal)

= 5.34E+13

16 LIVESTOCK

Imports = 1.18E+08 avg. total weight

Energy (J)

= (_lb)*(453.6 g/lb)*(4 kcal/g)*(4186J/g)

= 9.00E+12

17 FOODS

Imports = 9.29E+05 m^3

Energy (J)

= (_ m^3)*(0.5E+06 g/m^3)*(3.6kcal/g)*(4186J/kcal)

= 7.00E+13

18 PLASTICS & RUBBER

Imports = 2.46E+08 kg

Energy (J)

= (_kg)(9.4e6J/kg)

= 2.31E+13

19 CHEMICALS

Imports = 1.59E+10 g

20 WOOD, PAPER, ETC.

Imports = 6.67E+05 MT

Energy (J)

= (_MT)*(1E6 g/MT)*(15E3 J/g)

= 1.00E+14

21 MECHANICAL & TRANSPORATION EQUIPMENT

Imports = 3.43E+09 g

22 SERVICES

= 9.87E+07 $

23 TOURISM

= 3.73E+08 $

Table C-4. --continued.

24 CASH CROPS		
Exports		= 4.55E+05 m^3
	Energy (J)	
		= (_ m^3)*(0.5E+06 g/m^3)*(3.6kcal/g)*(4186J/kcal)
		= 3.26E+15
25 OIL DERIVED PRODUCTS		
Exports		= 3.36E+08 BBL
	Energy (J)	
		= (_BBL)*(6.28E9 J/BBL)
		= 2.11E+16
26 MINERALS		
Exports		= 4.92E+09 g
27 CHEMICALS		
Exports		= 1.07E+10 g
28 SERVICES IN EXPORTS		
		= 2.63E+07 $
29 TOURIST SERVICE		
		= 5.15E+06 $

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I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.

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